



WallyPacholka / AstroPics.com



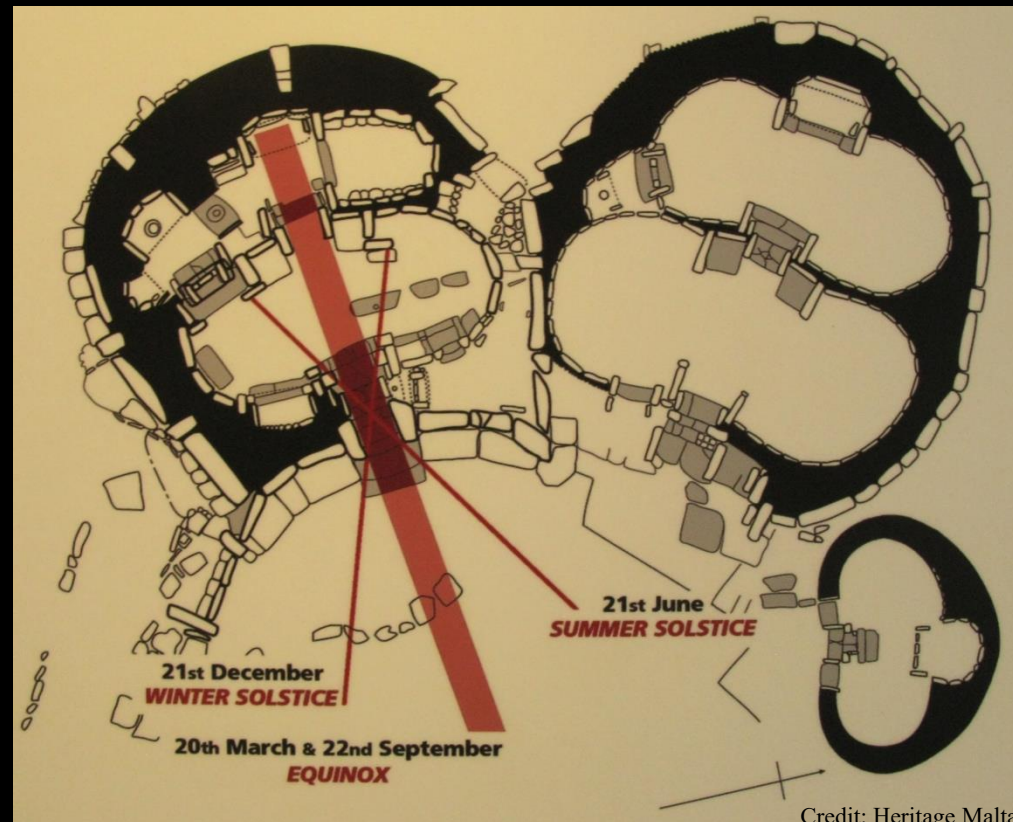
# Astrometry goes back over 5000 years!

Credit: Heritage Malta

Island of Malta  
Ggantija ~3500 B.C.  
Mnajdra ~3200 B.C.



Mnajdra solar alignments

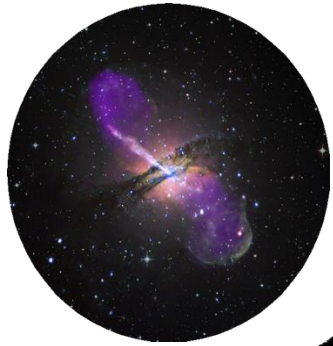


Credit: Heritage Malta

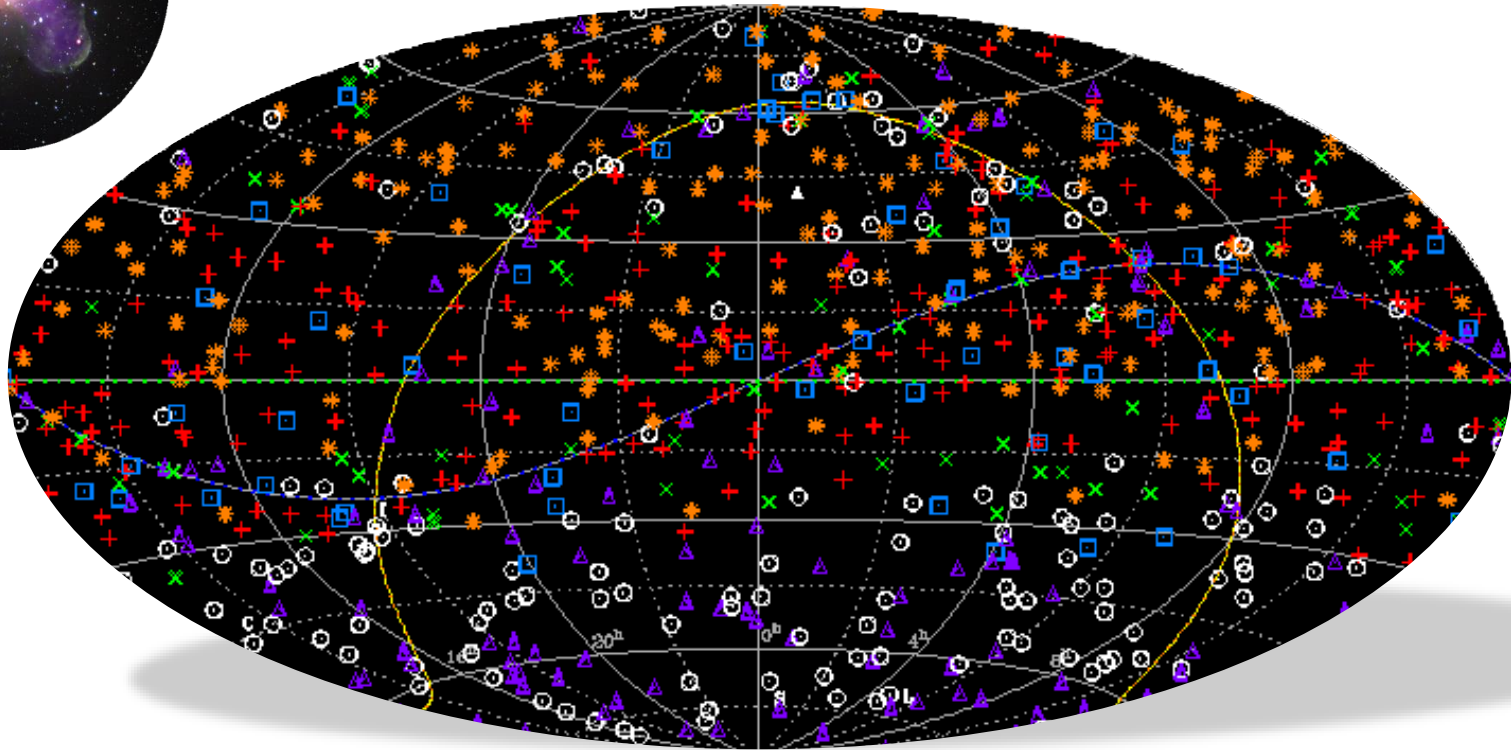
Mnajdra,  
Malta



AVN School-2018, *Hartebeesthoek, South Africa*



# Celestial Reference Frames



Christopher S. Jacobs

Jet Propulsion Laboratory, California Institute of Technology

2018 March 21



# Outline

## I. Concepts and Background:

- A. What is a Reference frame? Concepts, uses, desired properties
- B. Networks: The instruments used to build the frame  
ad hoc, VLBA, EVN, Global, NASA-ESA DSN, LBA, AuScope, etc.
- C. Brief history of Astrometry: The 'fixed' stars aren't so fixed.
  - 1. Precession, proper motion, nutation, parallax
  - 2. Invention of radio astronomy. VLBI's pursuit of (sub)milli-arcsecond accuracy.

## II. Celestial Frames built using *Very Long Baseline Interferometry* (VLBI)

- A. Surveys: Single dish, connected array: JVAS, AT20G, and VLBI: VCS, LCS
- B. ICRF-1, ICRF-2: The IAU moves to from optical (stars) to radio (quasars)
- C. Higher frequency radio frames: K&Q (24 & 43GHz), X/Ka (32 GHz)

## III. The Path to the Future:

- A. Error Budgets: a tool for allocating resources for improvement
- B. Case study: Path to Improved X/Ka (8.4/32 GHz) Frame
- C. ICRF-3: the next standard radio frame
- D. Gaia: an optical frame with high accuracy, billion sources



# I. A. Concepts for Celestial Frames

## 1. Questions:

Why do we need reference frames? Celestial Frames?  
Time, positions, velocities

## 2. The Celestial Frames

Terrestrial:	Azimuth,	Elevation
Equatorial plane:	Right Ascension	& Declination
Ecliptic Plane:	Ecliptic Longitude	& Latitude
Galactic Plane:	Galactic Longitude	& Latitude

## 3. Inertial Frames

**approximate point sources at infinity**

No rotation

No acceleration

Quasi-inertial



# I. A.1 Why a Celestial Frame?

---

Questions:

Why do we need reference frames? Celestial Frames?

To measure Time, positions, and velocities

Time: The rotation of the earth

Positions & velocities:

Angular positions and distances of

Quasars, galaxies, stars, planets, spacecraft





# I. A.2 The Celestial Sphere

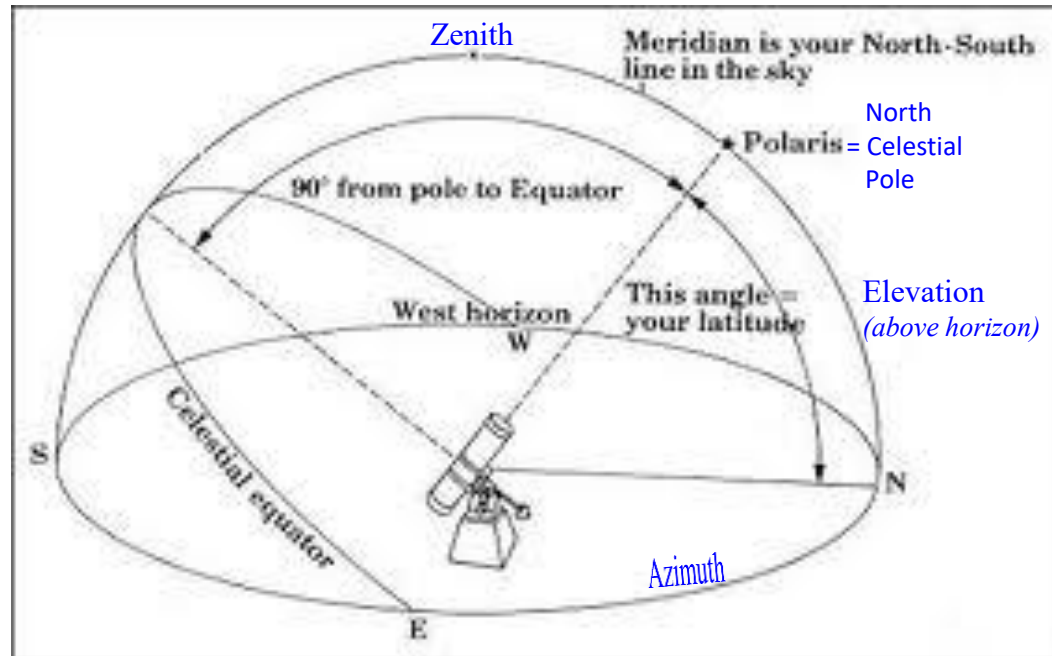
Preferred Frame changes with scale and application

- **Local terrestrial:** Elevation, Azimuth  
Local gravity or normal to horizon gives preferred direction  
Useful for antenna pointing
- **Equatorial plane:** Right Ascension & Declination  
Earth's spin gives preferred direction
- **Ecliptic Plane:** Ecliptic longitude & latitude  
plane of solar system, planetary orbits  
useful for studying the solar system and  
inter-planetary navigation
- **Galactic Plane:** Galactic Longitude & latitude  
plane of Milky Way galaxy  
Useful for pulsars, masers, rotation curves...
- **Even larger structure:** local group of galaxies, Virgo cluster, ...



## I. A.2 Local Horizon: Azimuth, Elevation

- Local terrestrial: **Elevation, Azimuth**  
Local gravity or normal to horizon gives preferred direction  
Useful for antenna pointing







# I. A.2 The Celestial Sphere

## Equatorial System:

Earth's spin axis gives preferred direction, the celestial pole

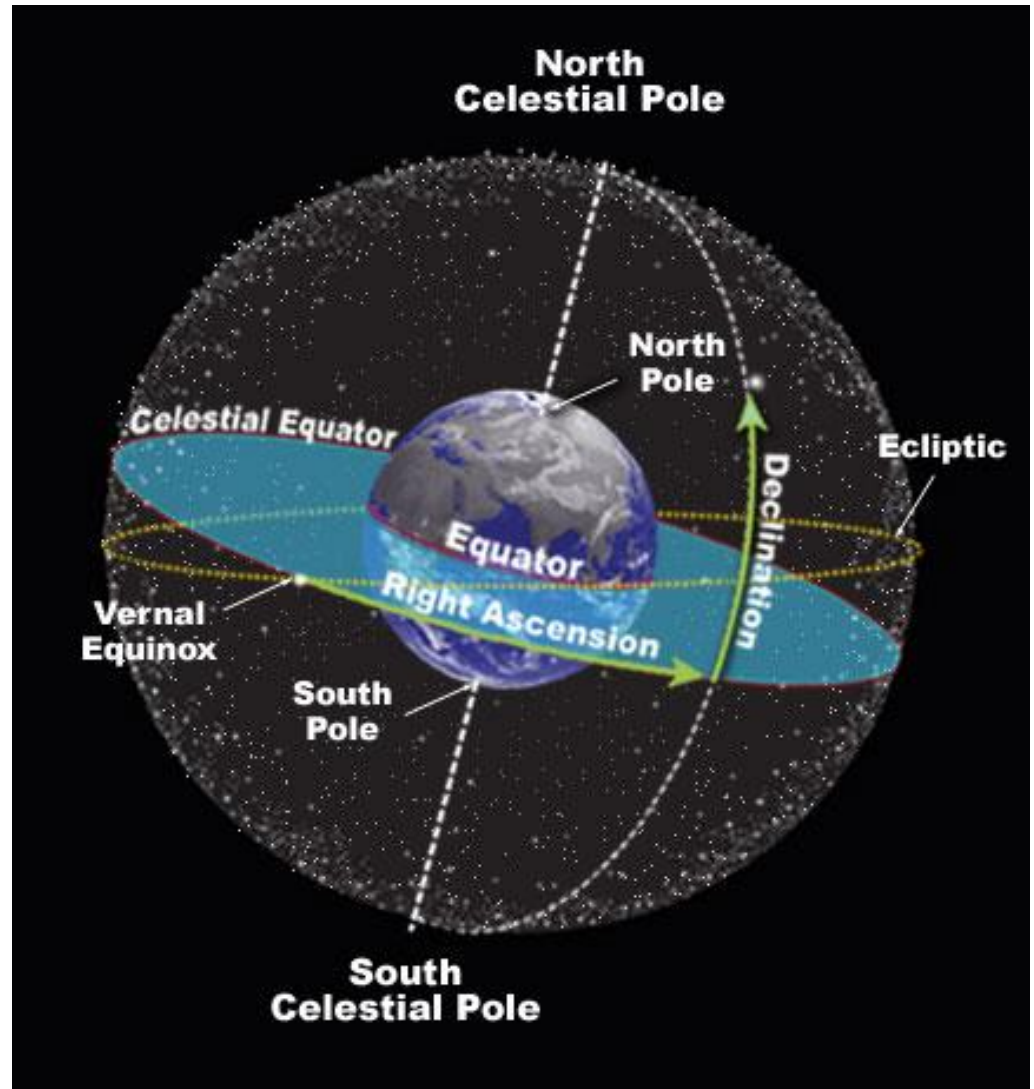
## Coordinates on the sky:

Right Ascension (“longitude”)

Declination (“latitude”)

## Ecliptic Plane:

Ecliptic Longitude & Ecliptic Latitude  
plane of solar system  
useful for studying the solar system and inter-planetary navigation



Credit: <http://www.daviddarling.info/encyclopedia/C/celsphere.html>



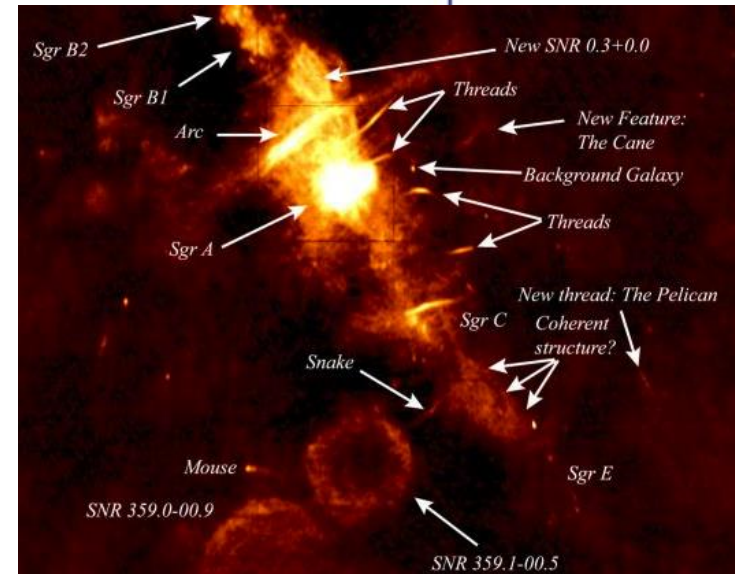
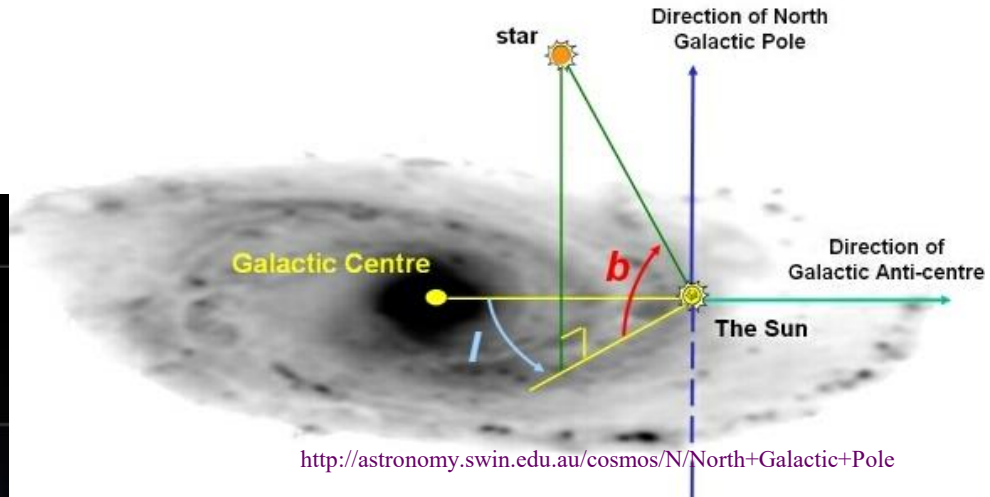
# I. A.2 The Celestial Sphere

- Galactic Plane: Galactic Longitude,  $l$ , & Galactic latitude,  $b$   
Useful for pulsars,  
masers, rotation curves...



Credit: Robert Hurt & NASA

<http://tracingknowledge.wordpress.com/tag/milky-way/>



Galactic center: VLA radio image

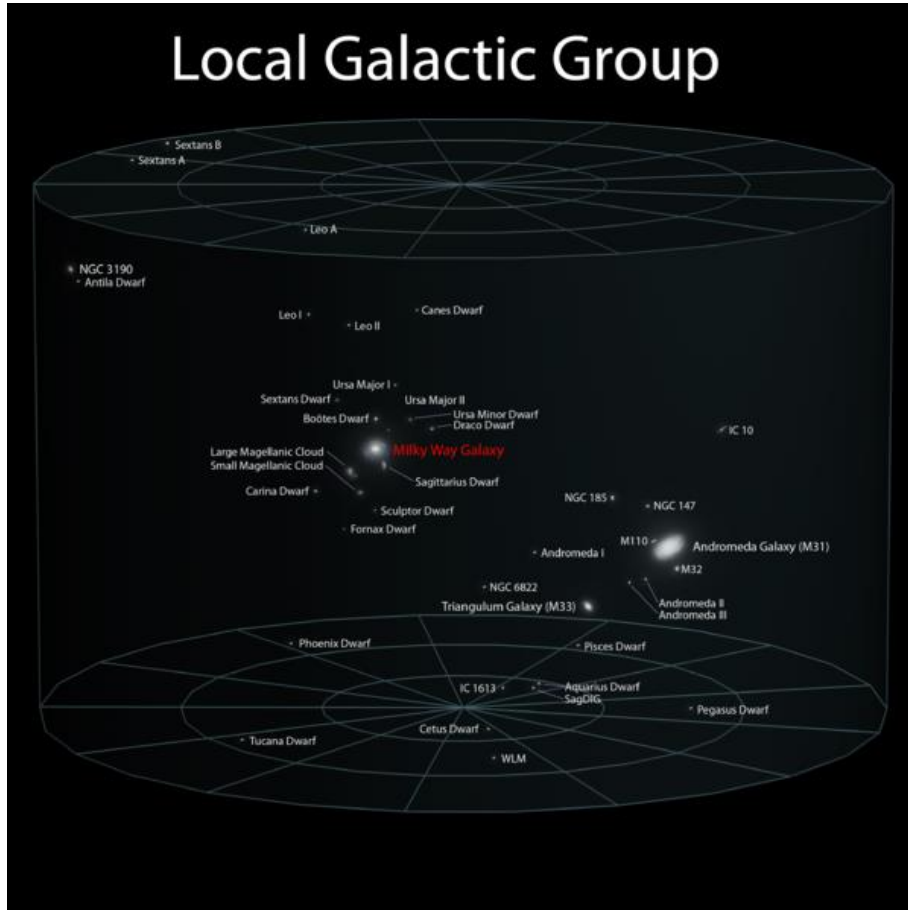
Kassim, NRAO. <http://images.nrao.edu/326>



# I. A.2 The Celestial Sphere

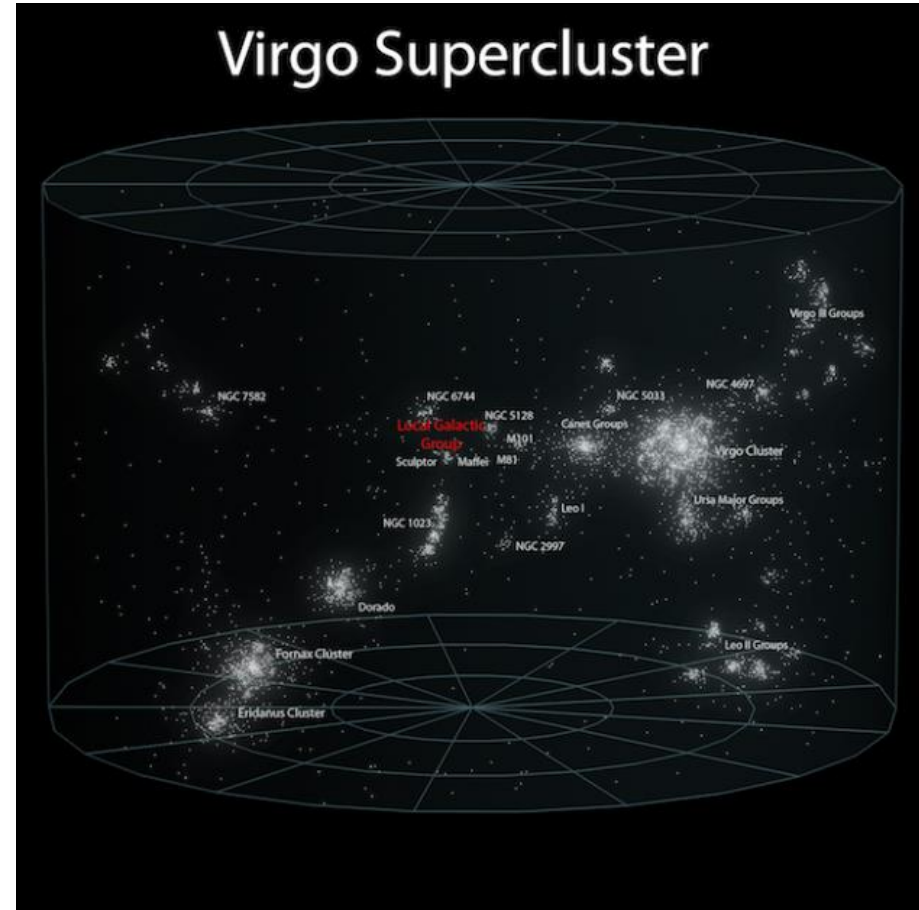
- How far before we get to the quasars? Even larger structures: local group of galaxies, Virgo cluster, Virgo super cluster...

## Local Galactic Group



~3 Million light years

## Virgo Supercluster



~100 Million light years

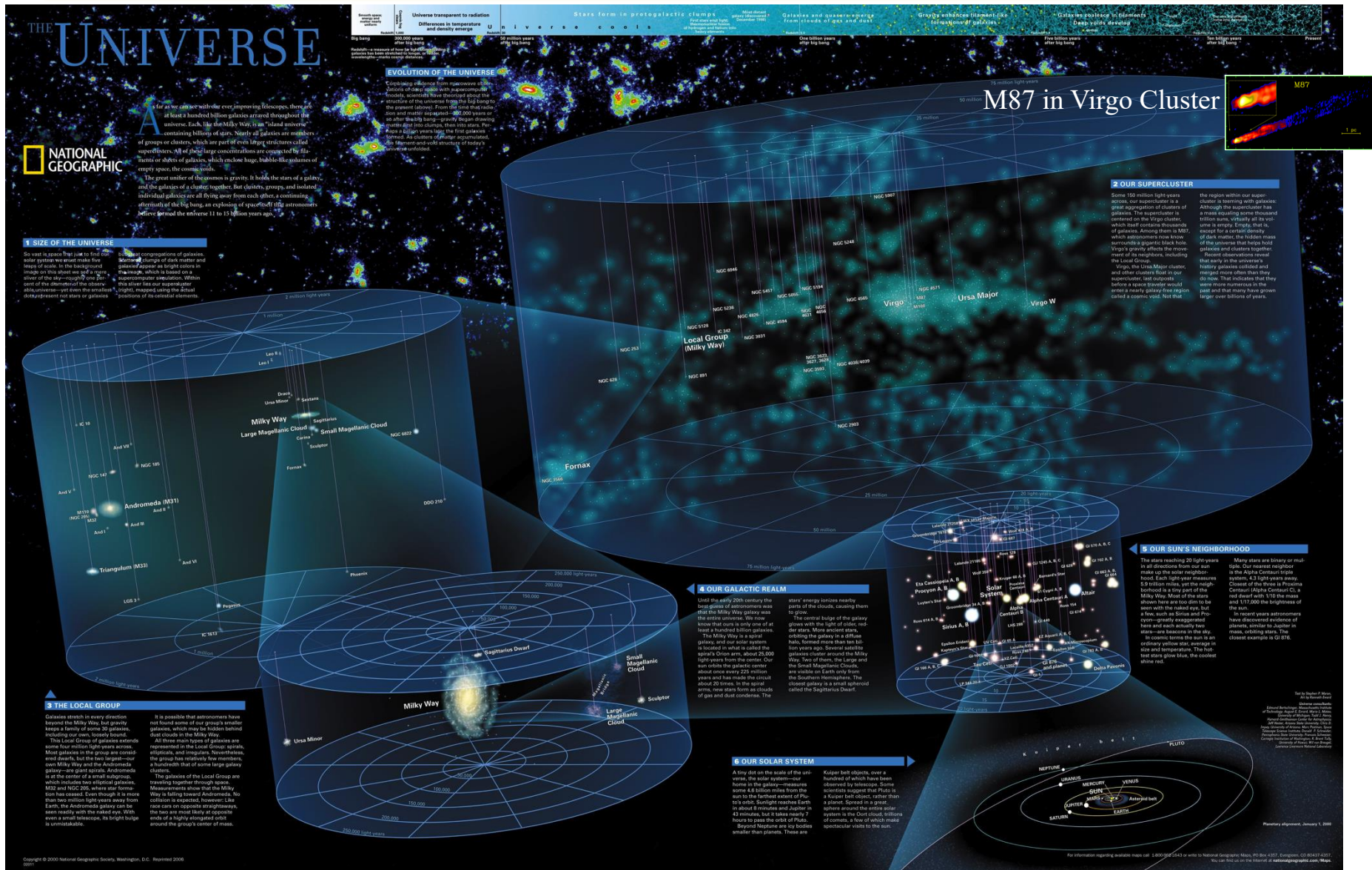
Credit: Andrew Z. Colvin

[http://commons.wikimedia.org/wiki/File%3AEarth's\\_Location\\_in\\_the\\_Universe\\_\(JPEG\).jpg](http://commons.wikimedia.org/wiki/File%3AEarth's_Location_in_the_Universe_(JPEG).jpg)





# Quasars ~ Giga-parsec; Virgo cluster distance (50 Mpc)





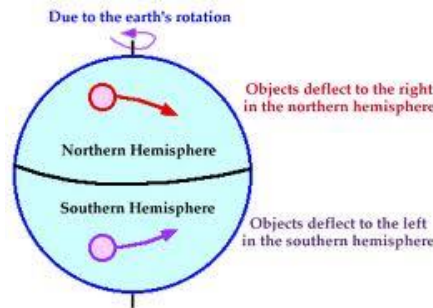


## I. A.3 Inertial Frames

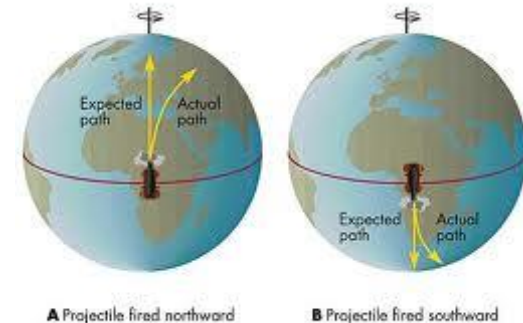
- Why an Inertial Frame?  
Make the calculations easy! Avoid Coriolis forces etc.

No rotation

No acceleration



Univ. Illinois WW2010 Project  
[http://ww2010.atmos.uiuc.edu/\(Gh\)/guides/mtr/fw/crls.rxml](http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/fw/crls.rxml)



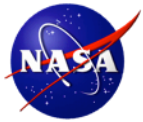
- Quasi-inertial  
In real systems we have some unmodeled accelerations  
At present, VLBI doesn't yet model acceleration toward the Galactic center, but this is being studied  
e.g. Titov et al <http://arxiv.org/pdf/1301.0364v1.pdf>
- VLBI uses quasi-inertial frame with origin at the Solar System Barycenter (center of mass)





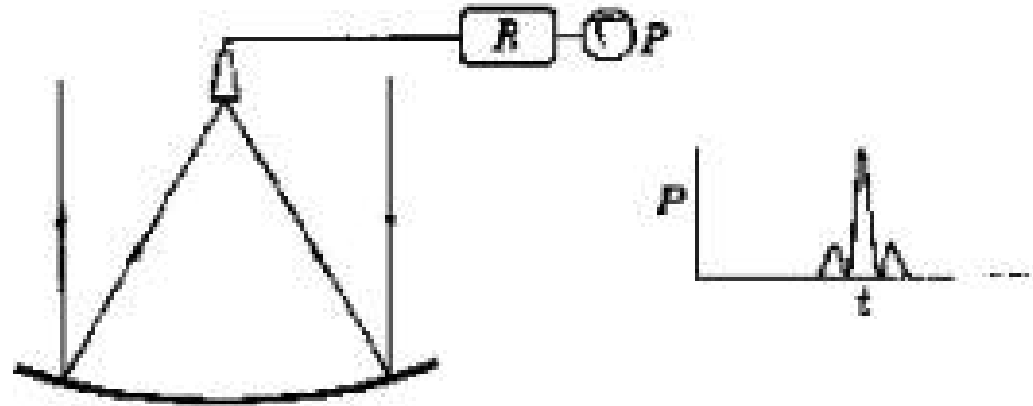
# How Does VLBI Work?

*Combine signals  
from a  
Phased Array*



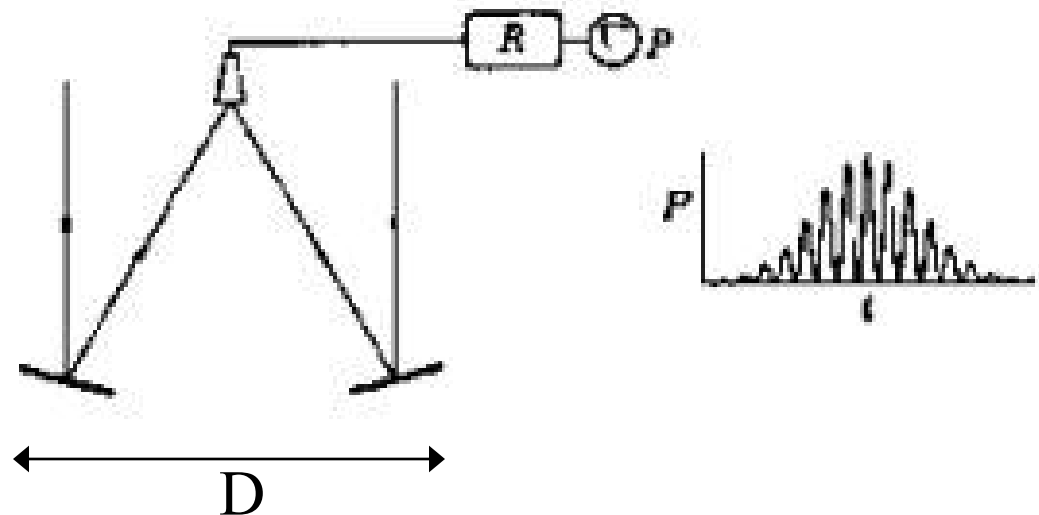
# Antennas are Mechanical Arrays

Single Large Dish  
is an “array” of  
panels aligned  
mechanically.  
Note side lobes.



beam

Imagine removing  
inner panels, then  
beam pattern changes,  
sidelobes rise, but  
center lobe still has  
high resolution  
 $\sim \text{wavelength} / D$

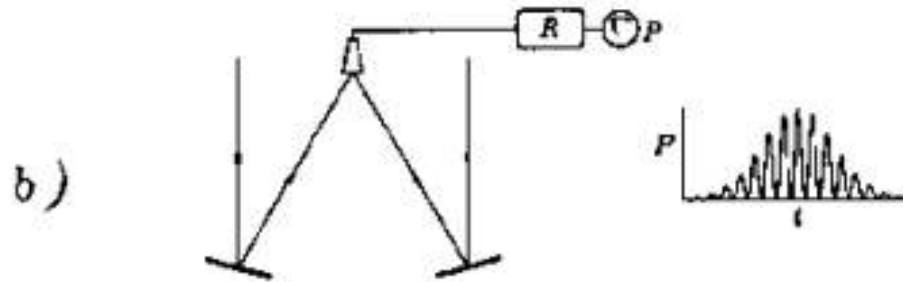






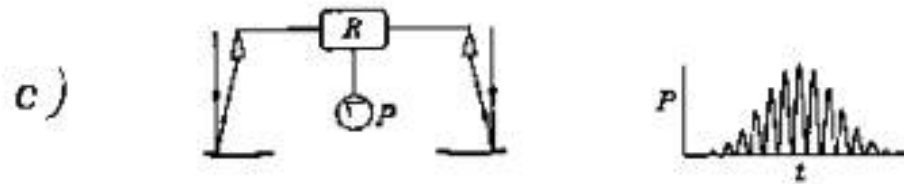
# Mechanical → electrical alignment → VLBI

Two segments  
of antenna



“Fringes”

Two separate  
antennas with  
Electrical  
Connection

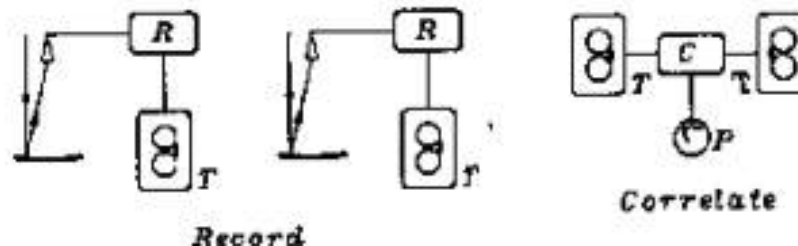


Same fringes  
as b).

Unconnected  
Antennas = VLBI

Time tag data and  
combine signals later at correlator

d)



Same fringes  
as b).

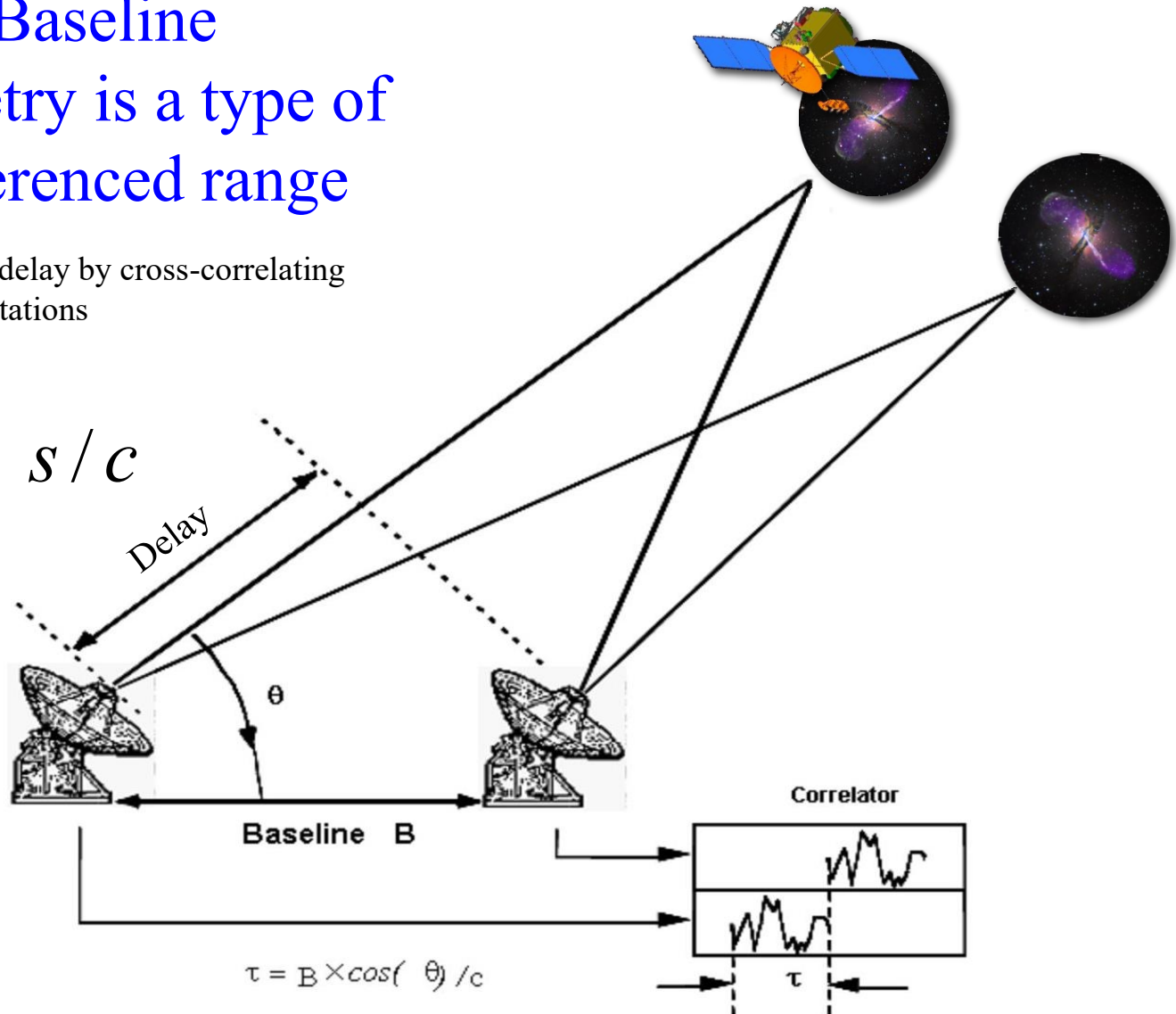


# VLBI Delay: $t = B \cdot s / c$

## Very Long Baseline Interferometry is a type of station differenced range

- Measures geometric delay by cross-correlating signal from two (2) stations

$$t = B \cdot s / c$$





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# I.B. Observing Networks

## VLBA

S/X VCS catalog

K, Q catalogs

25-meter dishes

10 stations

Baselines up to  
8000 km

No southern  
stations



Very Large Baseline Array <http://www.vlba.nrao.edu/>





# I.B. Observing Networks: EVN

EVN

S/X-band

K-band

Inhomogeneous  
set of antennas

+ HartRAO,  
South Africa



European VLBI Network <http://www.evlbi.org/>

# I.B. Observing Networks: Global



Map credit: Tae-Hyun, Jung (MPIfR, 2004)

<http://www3.mpifr-bonn.mpg.de/staff/tkrichbaum/Global-VLBI.html>





# Ka-band combined NASA/ESA Deep Space Net



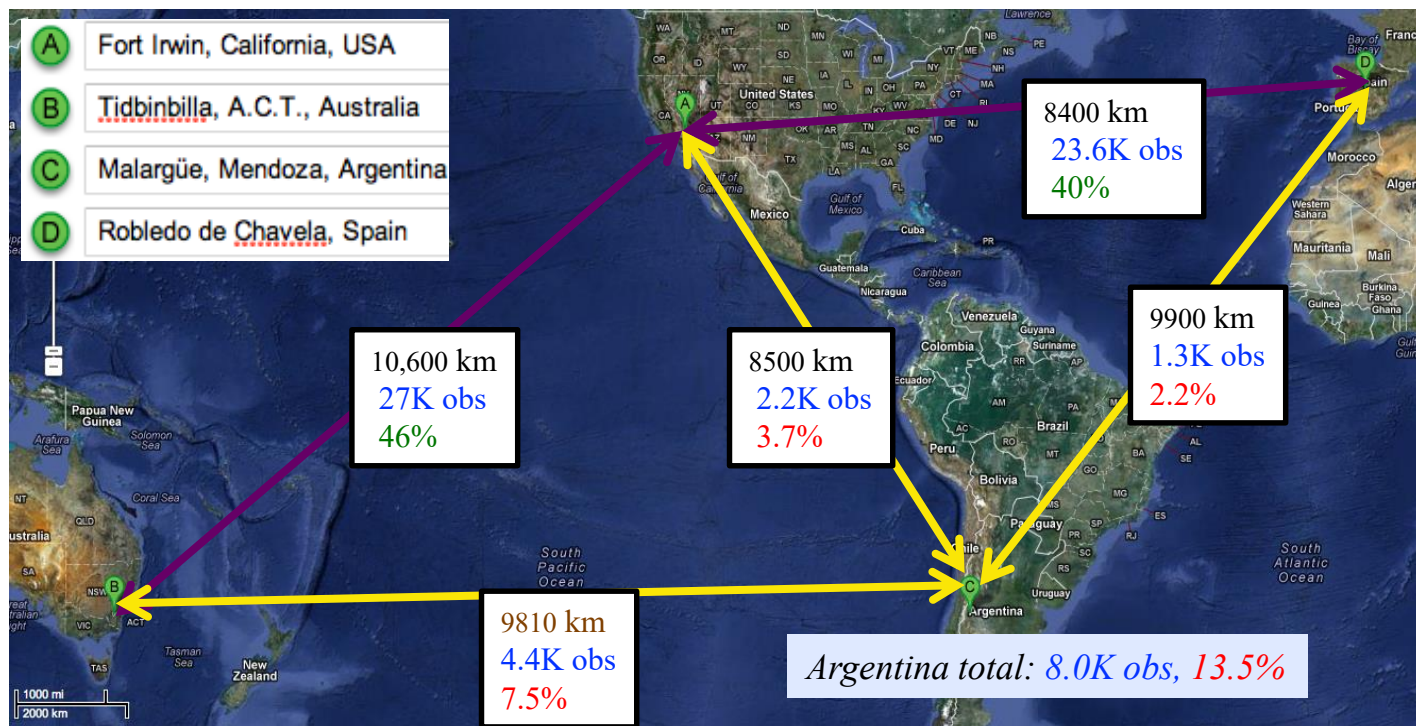
ESA Argentina to NASA-California under-observed by order of magnitude!

## Baseline percentages

- Argentina is part of 3/5 baselines or 60%  
but only 13% of obs
- Aust- Argentina 7.5%
- Spain-Argentina 2.2%
- Calif- Argentina 3.7%

This baseline is under-observed by a factor of ~ 12.

More time on ESA's Argentina station would have a huge, immediate impact!!



Maps credit: Google maps

- ESA's Argentina 35-meter antenna **adds 3 baselines** to DSN's 2 baselines
- Full sky coverage by accessing south polar cap
  - near perpendicular mid-latitude baselines: CA to Aust./Argentina



# I.C. History of Astrometry

130 B.C.	Hipparchus	Precession	50 asec/yr
<i>Telescope era:</i>			
1718 A.D.	Halley	proper motions	1 asec/yr
1729	Bradley	annual aberration	20 asec
1730	Bradley	18.6yr nutation	9 asec
1838	Bessell	parallax	~ asec
1930s	Jansky, Reber	Radio astronomy	
1960s	several groups	Very Long Baseline Interferometry (VLBI) invented	
1970s	“	VLBI	sub-asec
1980s	“	“	few 0.001 asec
1990s	“	“	< 0.001 asec
2000s	“	“	~0.0001 asec
2010s	Gaia	Optical astrometry	70 $\mu$ as for Vmag=18 quasar
2010s	ICRF-3, ESA-DSN XKa		20-70 $\mu$ as? 0.3 Jy quasar





# Paradigm of “Sailing by the stars”

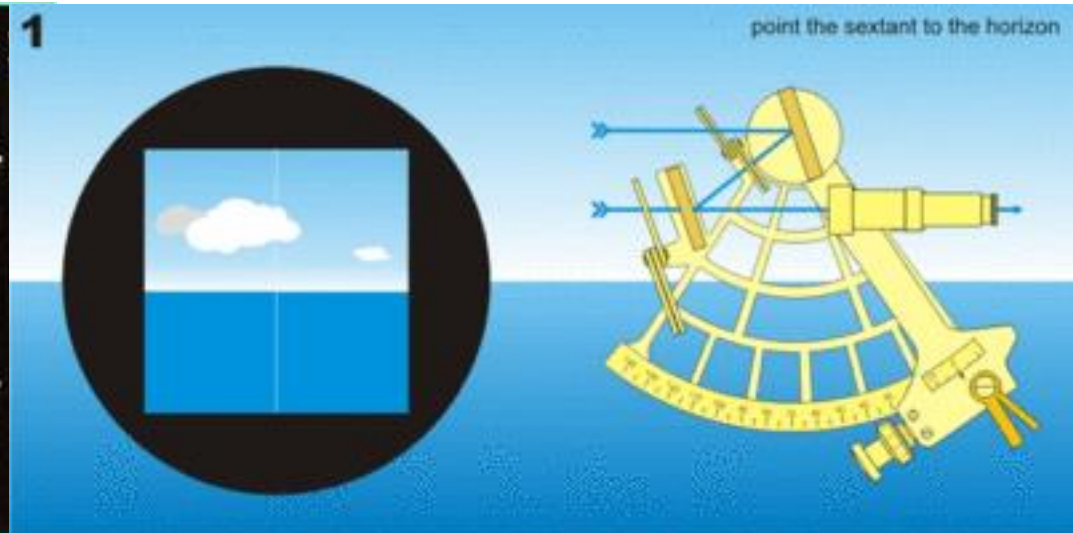
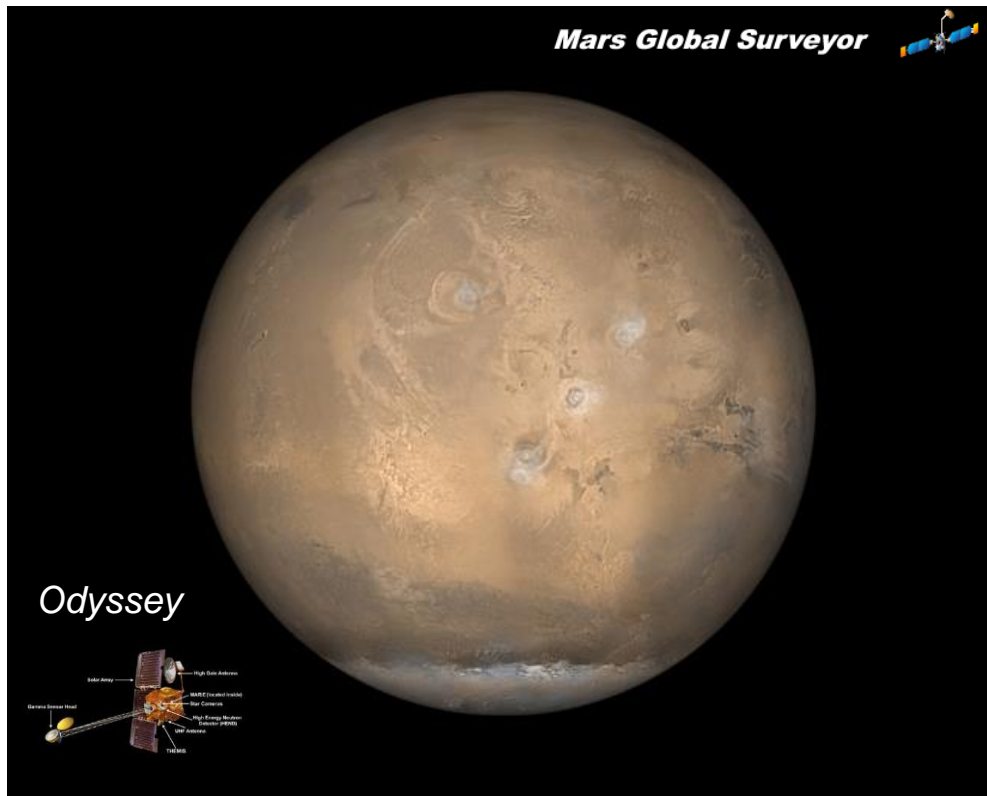
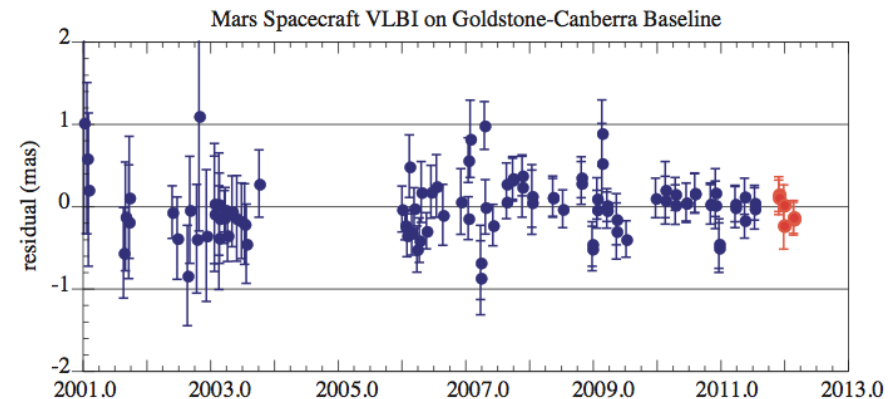
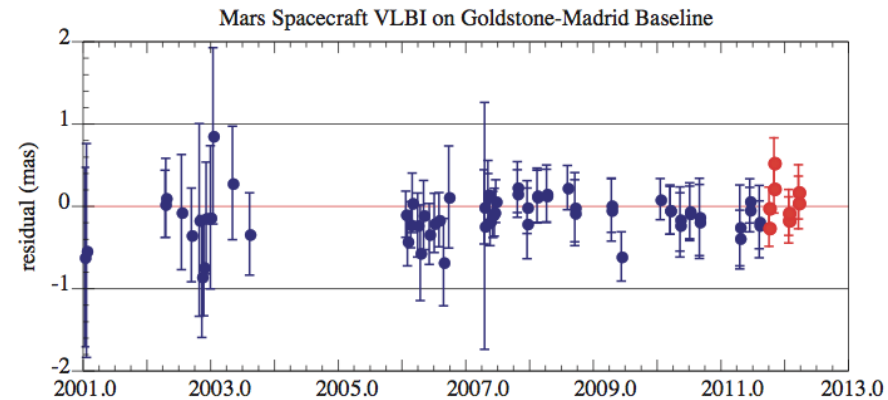


Photo Credit: Dmitry Bobroff, [www.ludmillaalexander.com](http://www.ludmillaalexander.com)



# Planetary Ephemeris to ICRF Frame Tie

- $\Delta$ VLBI measurements  
of spacecraft around a planet  
obtains position in the ICRF frame
- Doppler and range measures  
spacecraft in planet center Frame.



Folkner et al, IAU, Aug. 2012  
200  $\mu$ as (1. nrad) residuals

<http://referencesystems.info/uploads/3/0/3/0/3030024/folkner.pdf>  
<http://adsabs.harvard.edu/abs/2012IAUJD...7E..36F>



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C.S. Jacobs March 2018



# How Does VLBI Work?

*The Concept:*

**Point Source at Infinity**





# Point Source at Infinity as Reference Beacon

## How does VLBI work?

- Point source at infinity as a direction reference

Extragalactic “nebulae” idea from

Laplace (1749-1827) and

Wm. Herschel (1738-1822): *in 1785*

*realized that “nebulae” likely very distant*

*‘On the Construction of the Heavens,’ Ph.Trans.Roy.Soc., 1785, p. 213 ff.*

- Advantage: **sources don’t move**

**BUT** at a distance of a *billion* light years . . .

- The price to be paid is

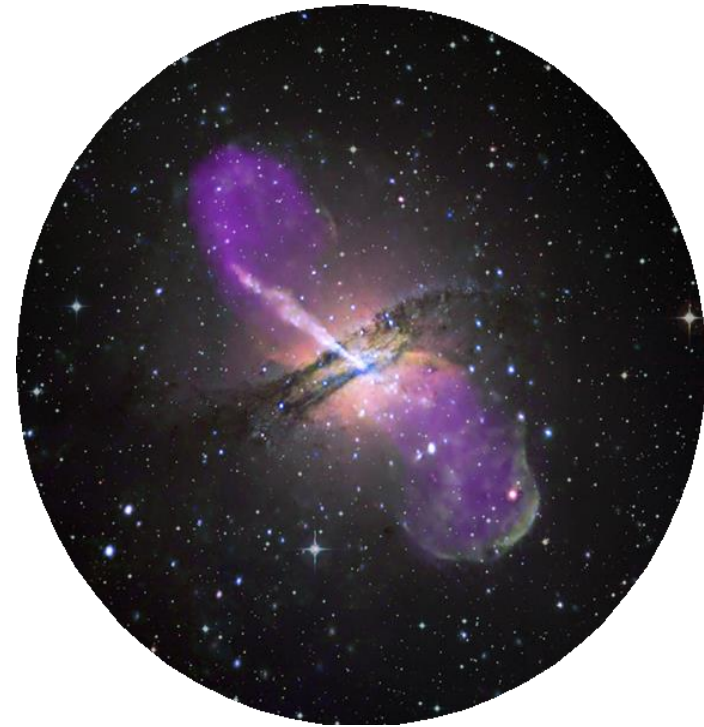
**Very weak sources**

**1 Jy =  $1.0\text{E-}26$  watt/m\*\*2/Hz**

**need lots of square meters => 34 - 70m Antenna**

**lots of Hz bandwidth => 0.1 to 4 Gbps**

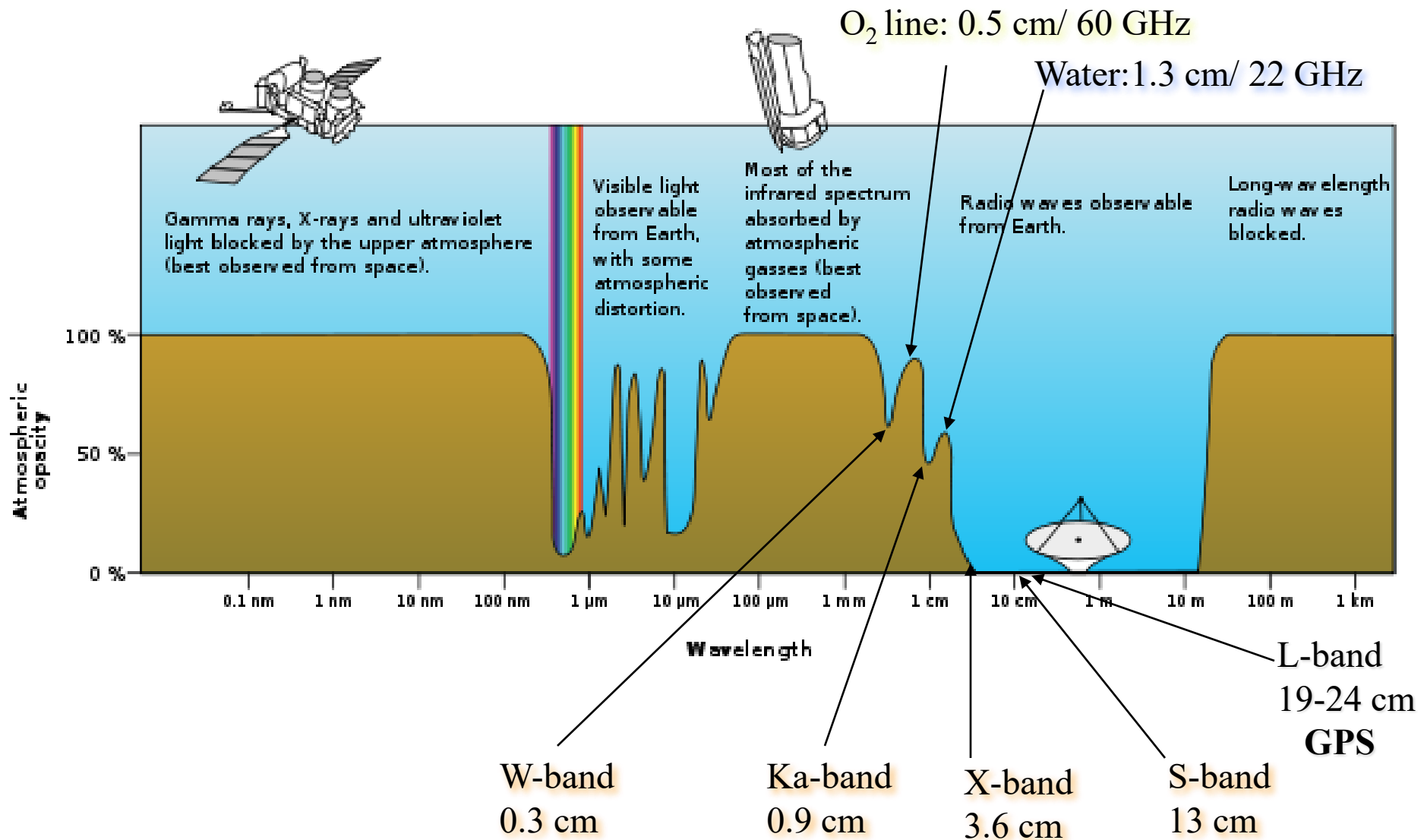
**low system temperature =>  $T_{\text{sys}} = 20 - 40$  Kelvin**



*Credit: chandra.harvard.edu/photo/2008/cena/cena\_multi.jpg*



# Why observe in Radio? The 'Window'



Credit: NASA; [http://en.wikipedia.org/wiki/Radio\\_window](http://en.wikipedia.org/wiki/Radio_window)



# Why observe in Radio? Resolution

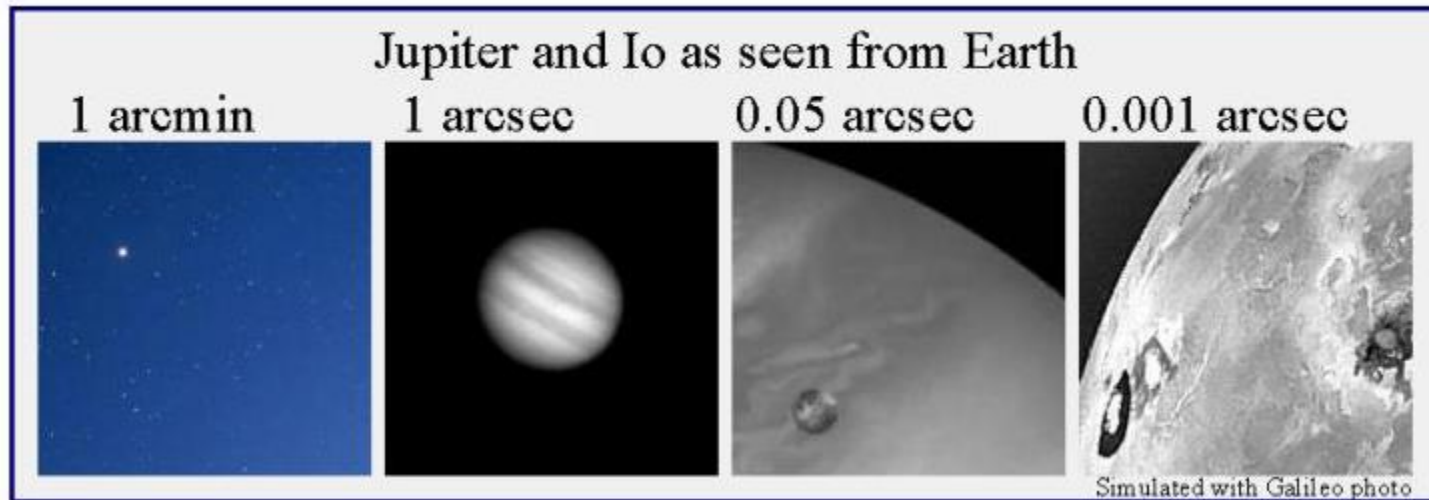
- Resolution of diffraction-limited telescope:  
Wavelength / Diameter  
*example:* Hubble Space Telescope  
Wavelength 0.1 to 2.5 microns  
Diameter 2.4 meters  
Resolution = 10 to 250 mas
- Resolution for an interferometer  
Wavelength / Baseline  
Wavelengths for Celestial Frames 0.9 to 3.6 cm  
Baselines up to 10,000 km  
Resolution = 1 to 4 nanoradians = 0.2 to 0.8 mas
- Radio has 50 times better resolution than Hubble.



# Why observe in Radio? Resolution

## THE QUEST FOR RESOLUTION

Resolution = Observing wavelength / Telescope diameter				
Angular Resolution	Optical (5000Å)		Radio (4cm)	
	Diameter	Instrument	Diameter	Instrument
1'	2mm	Eye	140m	GBT+
1"	10cm	Amateur Telescope	8km	VLA-B
0."05	2m	HST	160km	MERLIN
0."001	100m	Interferometer	8200km	VLBI
Atmosphere gives 1" limit without corrections which are easiest in radio				

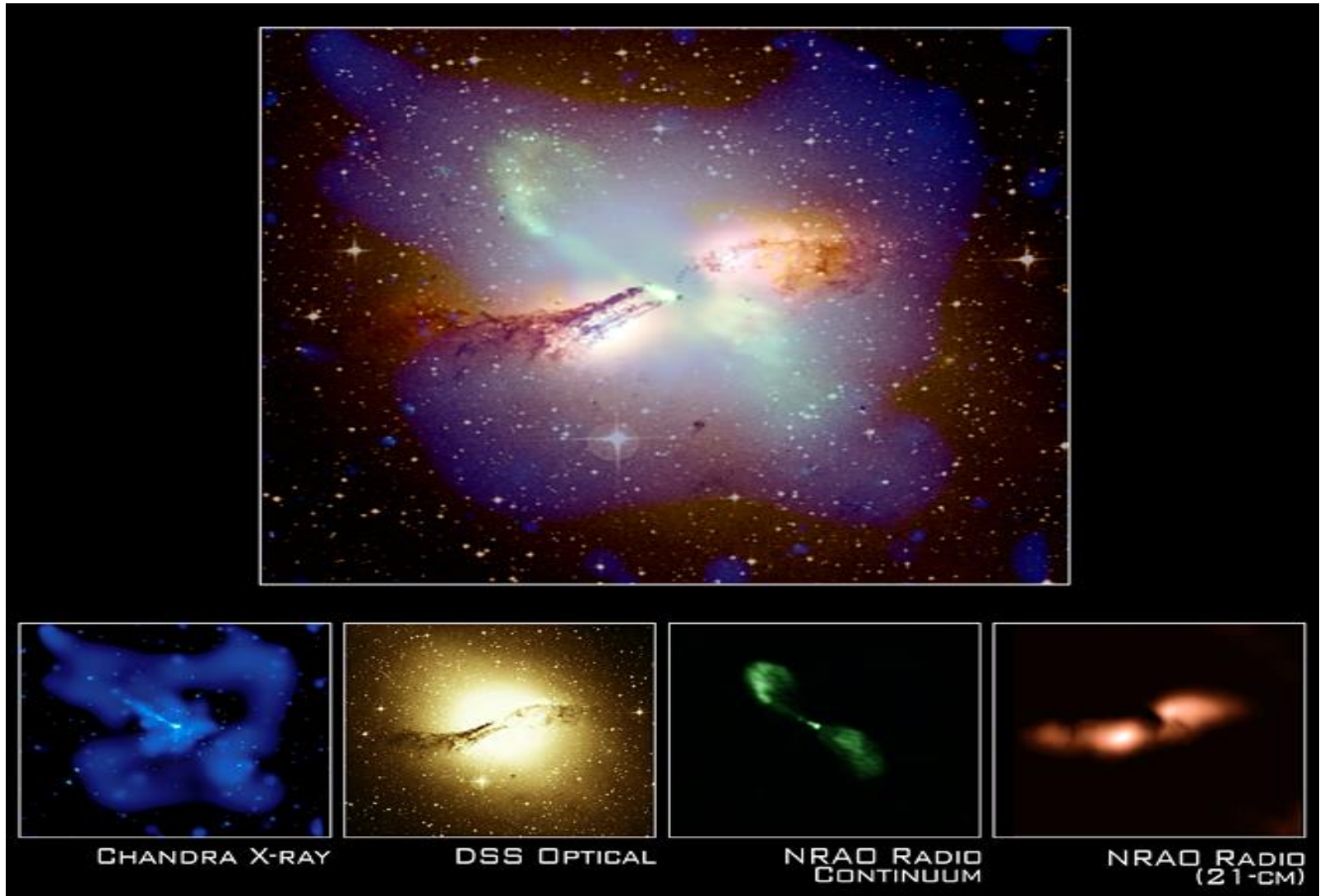


Credit: R. Craig Walker, NRAO, AAAS, 2001, [http://www.aoc.nrao.edu/~cwalker/talks/aaas\\_2001/sld002.htm](http://www.aoc.nrao.edu/~cwalker/talks/aaas_2001/sld002.htm)





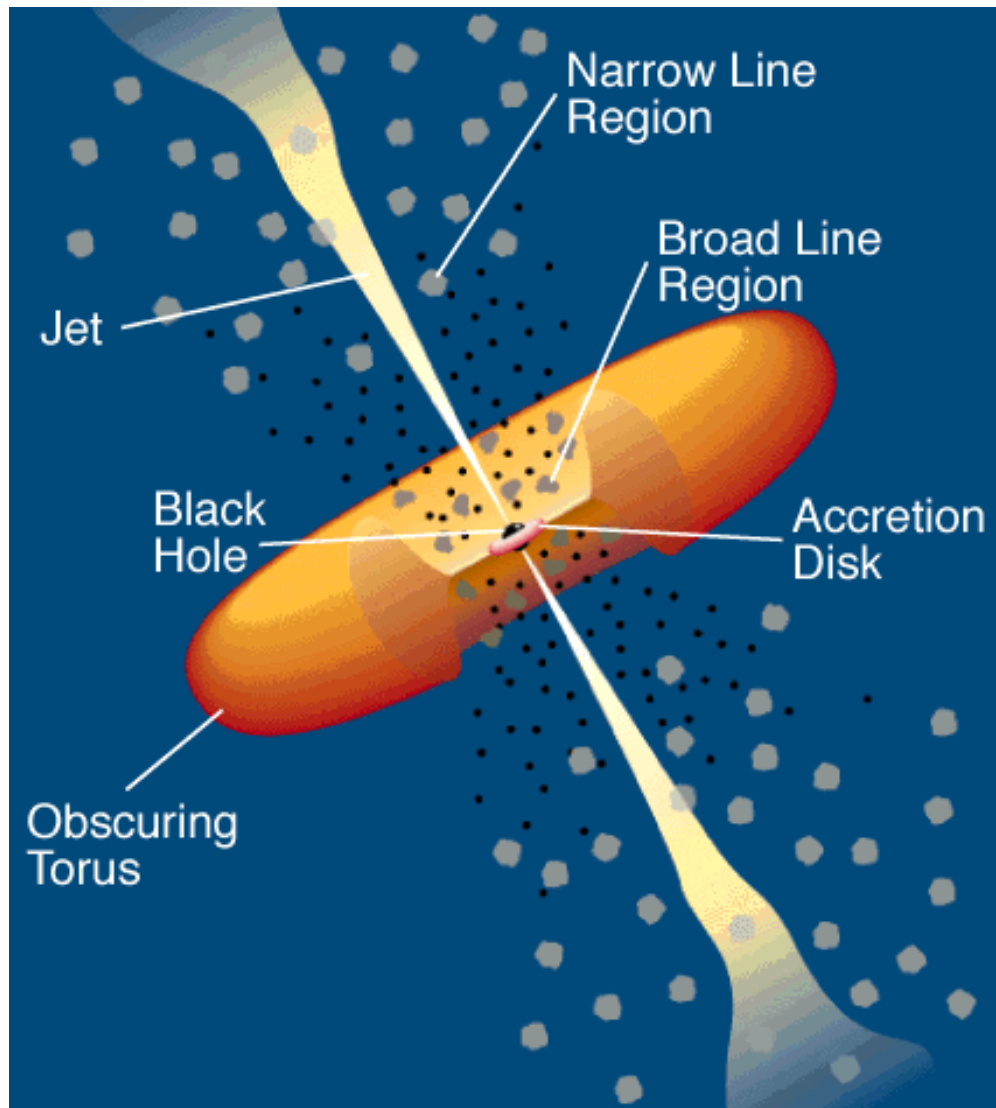
# AGN Centaurus-A in X-ray, Optical, Radio



Credits: X-ray (NASA/CXC/M. Karovska et al.); Radio 21-cm image (NRAO/VLA/Schiminovich, et al.),  
Radio continuum image (NRAO/VLA/J. Condon et al.); Optical (Digitized Sky Survey U.K. Schmidt Image/STScI)



# Active Galactic Nuclei (AGN) schematic



Schematic of  
*Active Galactic Nuclei*

Redshift  $z \sim 0.1$  to  $5$

Distance:  
billions light years

Parallax = 0

Proper motion  
 $< 0.1$  nrad/yr

Centroid of radiation  
Gets closer to central  
engine (black hole)  
As one goes to higher  
frequencies, therefore,

Ka-band (32 GHz)  
is better than  
X-band (8.4 GHz)

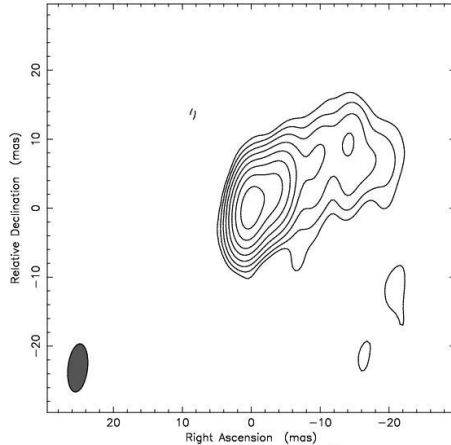
[http://heasarc.gsfc.nasa.gov/docs/objects/agn/agn\\_model.html](http://heasarc.gsfc.nasa.gov/docs/objects/agn/agn_model.html)

Credit: C.M. Urry and P. Padovani, 1995



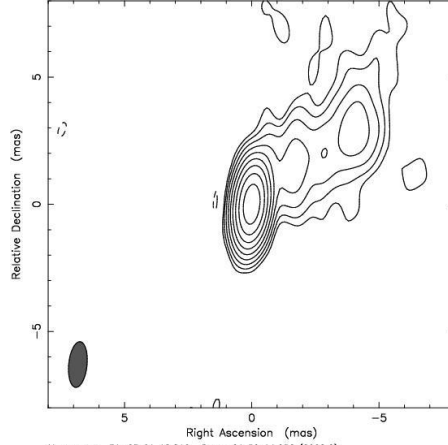
# Source Structure vs. Frequency (scaled to beam)

Clean RR map. Array: BFGGKLMNNOOPSTWKW  
0458-020 at 2.302 GHz 2002 Jan 16



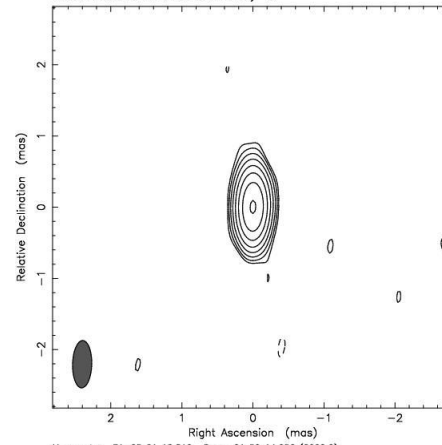
Map center: RA: 05 01 12.810, Dec: -01 59 14.256 (2000.0)  
Map peak: 0.415 Jy/beam  
Contours: 0.00195 Jy/beam x (-1 1 2 4 8 16 32 64)  
Contours: 128 J  
Beam FWHM: 7.01 x 2.85 (mas) at -6.43°

Clean RR map. Array: BFGGKLMNNOOPSTWKW  
0458-020 at 8.646 GHz 2002 Jan 16



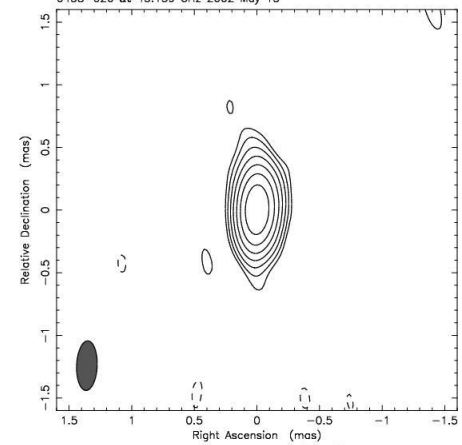
Map center: RA: 05 01 12.810, Dec: -01 59 14.256 (2000.0)  
Map peak: 0.727 Jy/beam  
Contours: 0.00168 Jy/beam x (-1 1 2 4 8 16 32 64)  
Contours: 128 J  
Beam FWHM: 1.8 x 0.719 (mas) at -5.72°

Clean RR map. Array: BFHKLMNOPS  
0458-020 at 24.439 GHz 2002 May 15



Map center: RA: 05 01 12.810, Dec: -01 59 14.256 (2000.0)  
Map peak: 0.896 Jy/beam  
Contours: 0.00664 Jy/beam x (-1 1 2 4 8 16 32 64)  
Contours: 128 J  
Beam FWHM: 0.665 x 0.269 (mas) at -1.46°

Clean RR map. Array: BFHKLMNOPS  
0458-020 at 43.139 GHz 2002 May 15



Map center: RA: 05 01 12.810, Dec: -01 59 14.256 (2000.0)  
Map peak: 0.664 Jy/beam  
Contours: 0.00533 Jy/beam x (-1 1 2 4 8 16 32 64)  
Contours: 128 J  
Beam FWHM: 0.396 x 0.164 (mas) at -2.32°

S-band  
2.3 GHz  
13.6cm

X-band  
8.6 GHz  
3.6cm

K-band  
24 GHz  
1.2cm

Q-band  
43 GHz  
0.7cm



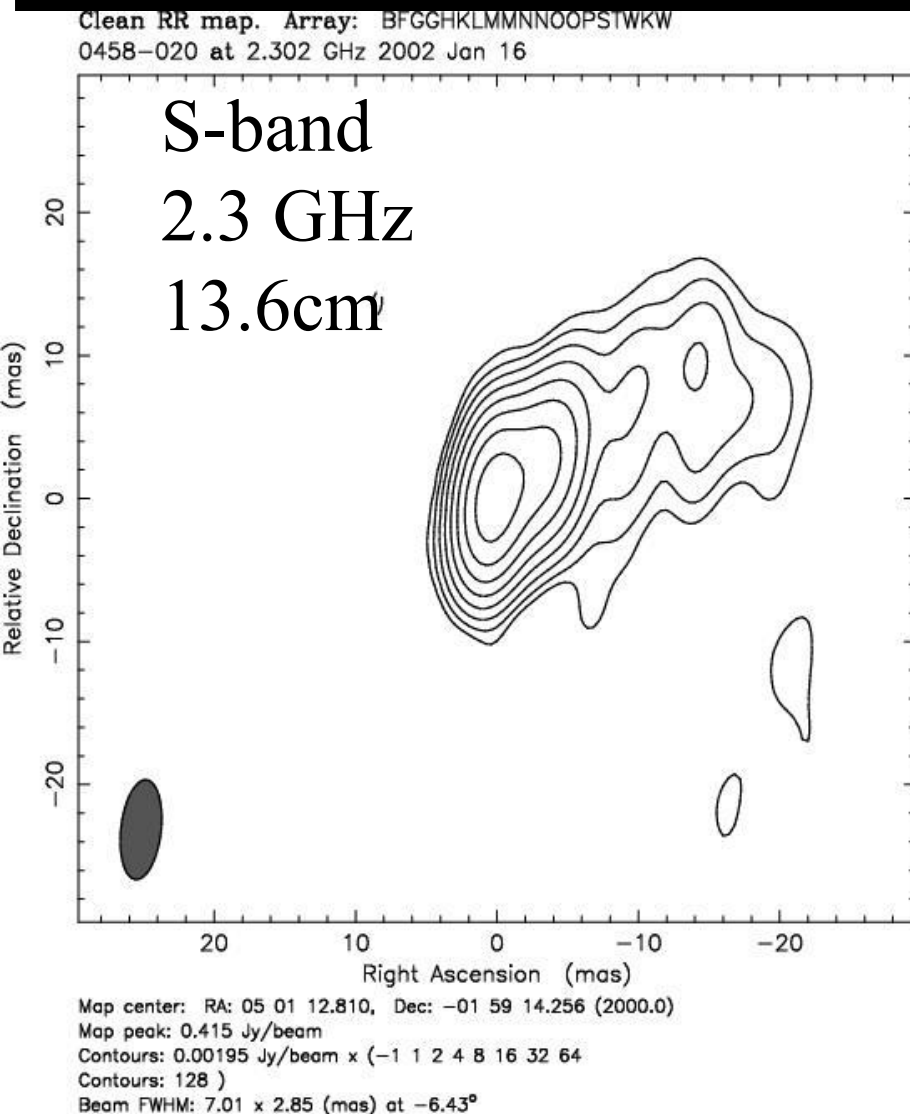
Ka-band  
32 GHz  
0.9cm

The sources become better ----->

Image credits: Pushkarev & Kovalev A&A, 544, 2012 (SX); P. Charlot et al, AJ, 139, 5, 2010



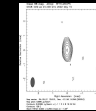
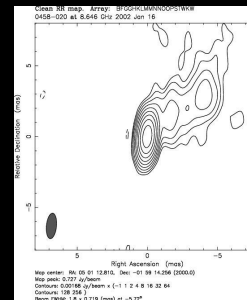
# Source Structure vs. Frequency (absolute scale)



**X-band**  
8.6 GHz  
3.6cm

**K-band**  
24 GHz  
1.2cm

**Q-band**  
43 GHz  
0.7cm



**The sources  
become better →  
smaller structure indexes  
(Fey & Charlot 1997)**

**Ka-band**  
32 GHz  
0.9cm



Images credit: Pushkarev & Kovalev A&A, 544, 2012 (SX); P. Charlot et al, AJ, 139, 2010

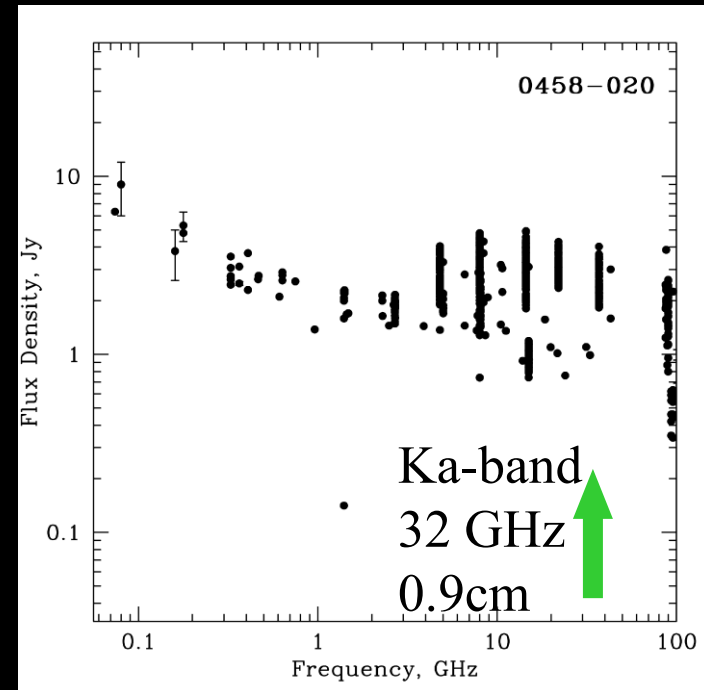
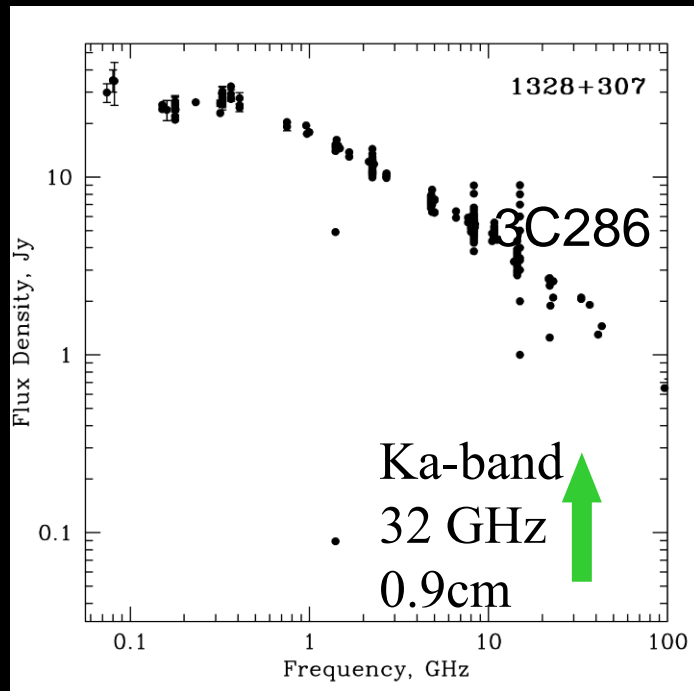




# Source Flux Density vs. Frequency

## Typical source emission:

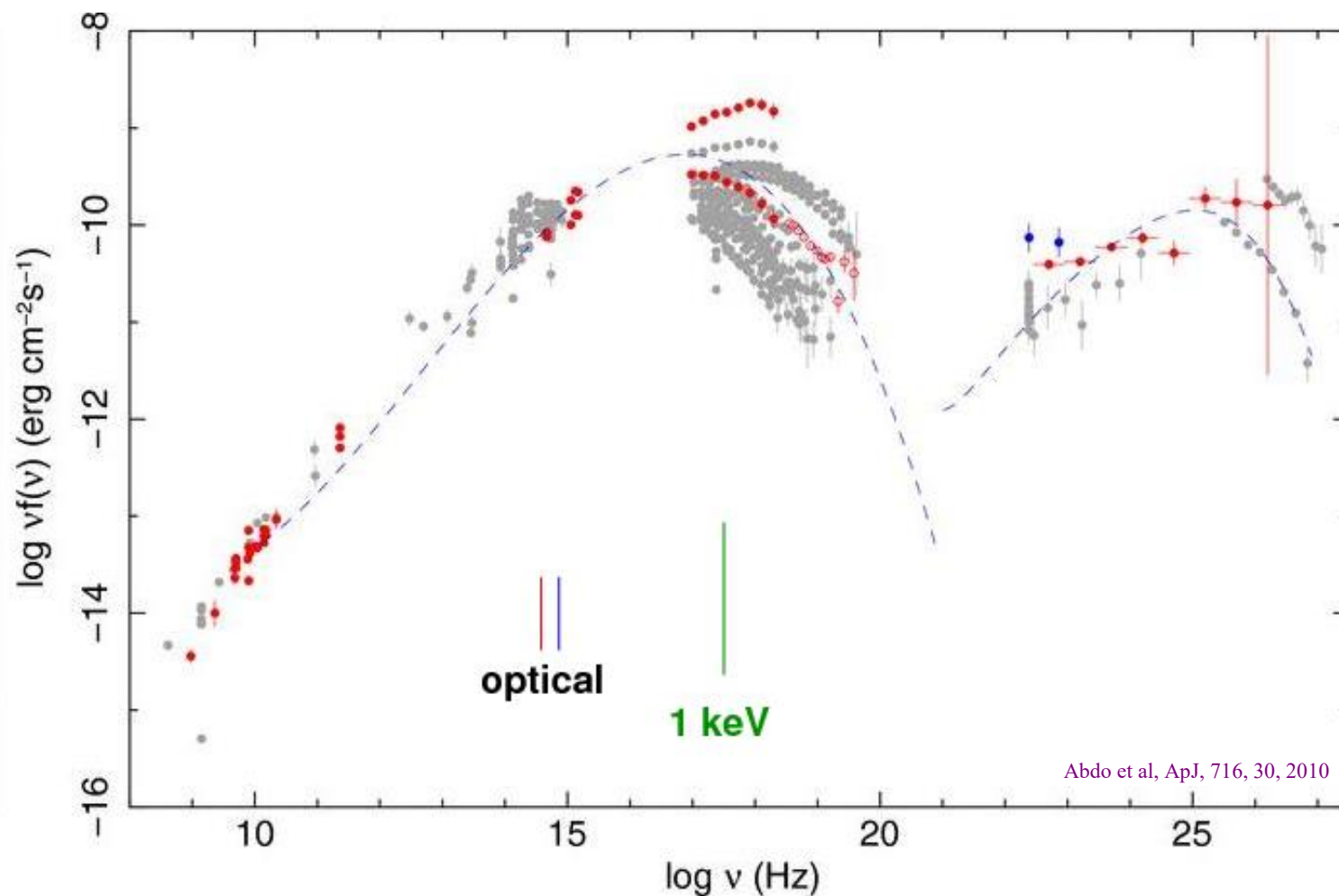
Generally emission decreases with frequency  
(steep spectrum), but not for all sources!  
and variable with time, but not for all sources!



*Images credit: MOJAVE project, Lister et al, AJ, 137, 2009*



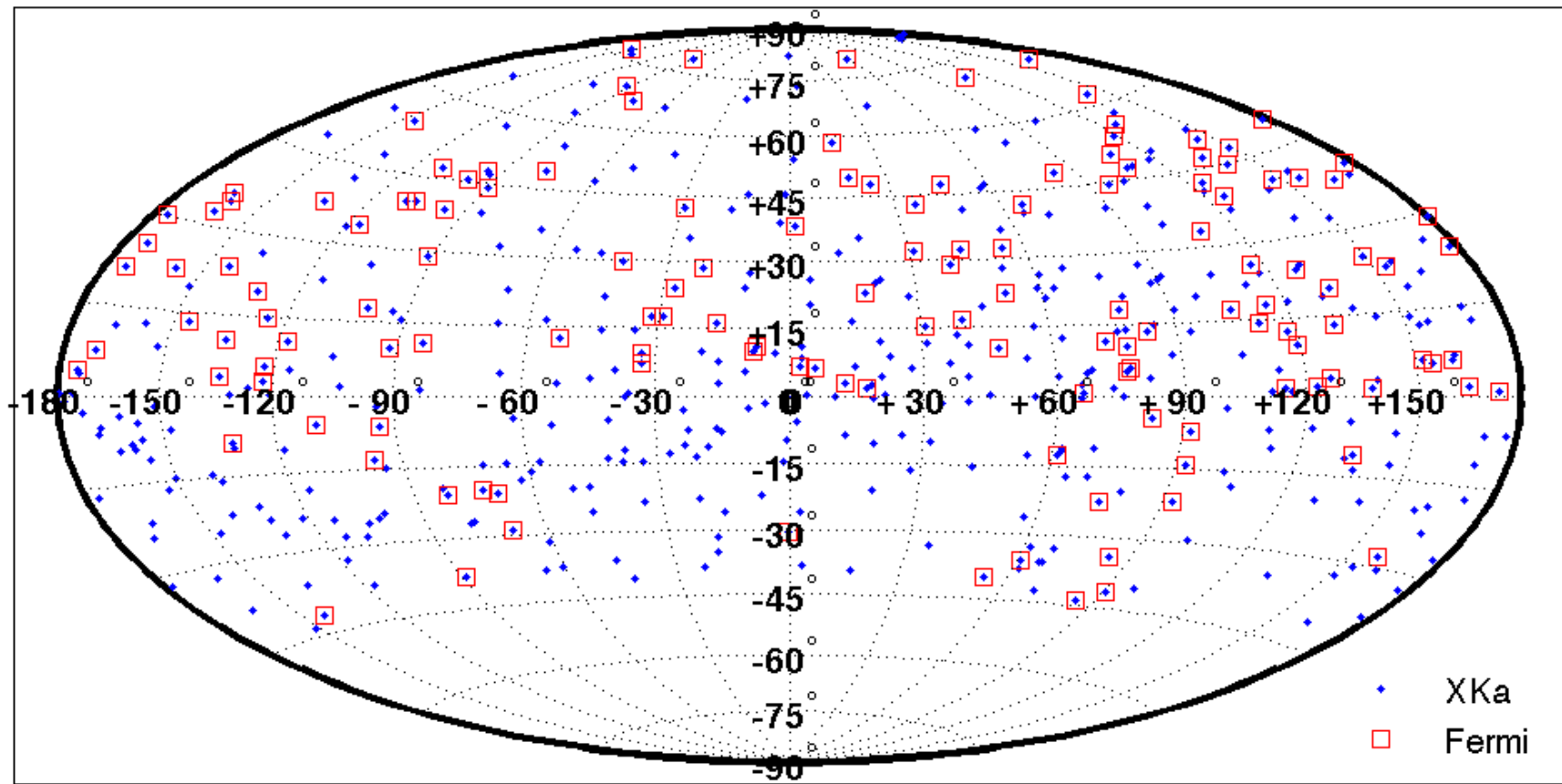
# Spectral Energy Distribution: Mkn 421



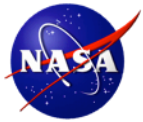
radio                      optical                      X-ray                      gamma  
synchrotron                      acc. disk. thermal                      inverse Compton



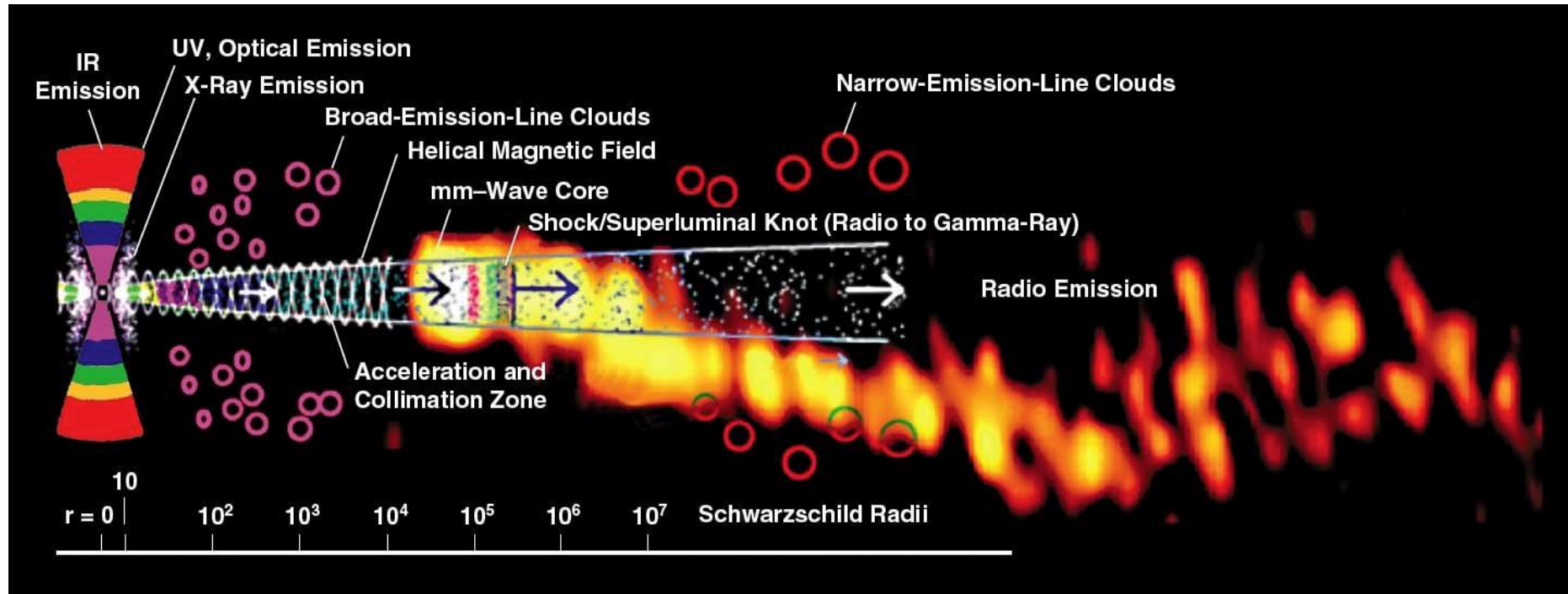
# X/Ka / FERMI gamma-ray correspondance



X/Ka sources (blue) which are surrounded by Red squares are also in the Fermi 2FGL gamma-ray point source catalog. Over 1/3 of X/Ka sources (~175) have gamma-ray detections.



# Active Galactic Nuclei (*Marscher*)



$R \sim 0.1 - 1 \mu\text{as}$

$1 \text{ mas}$

Features of AGN: *Note the Logarithmic length scale.*

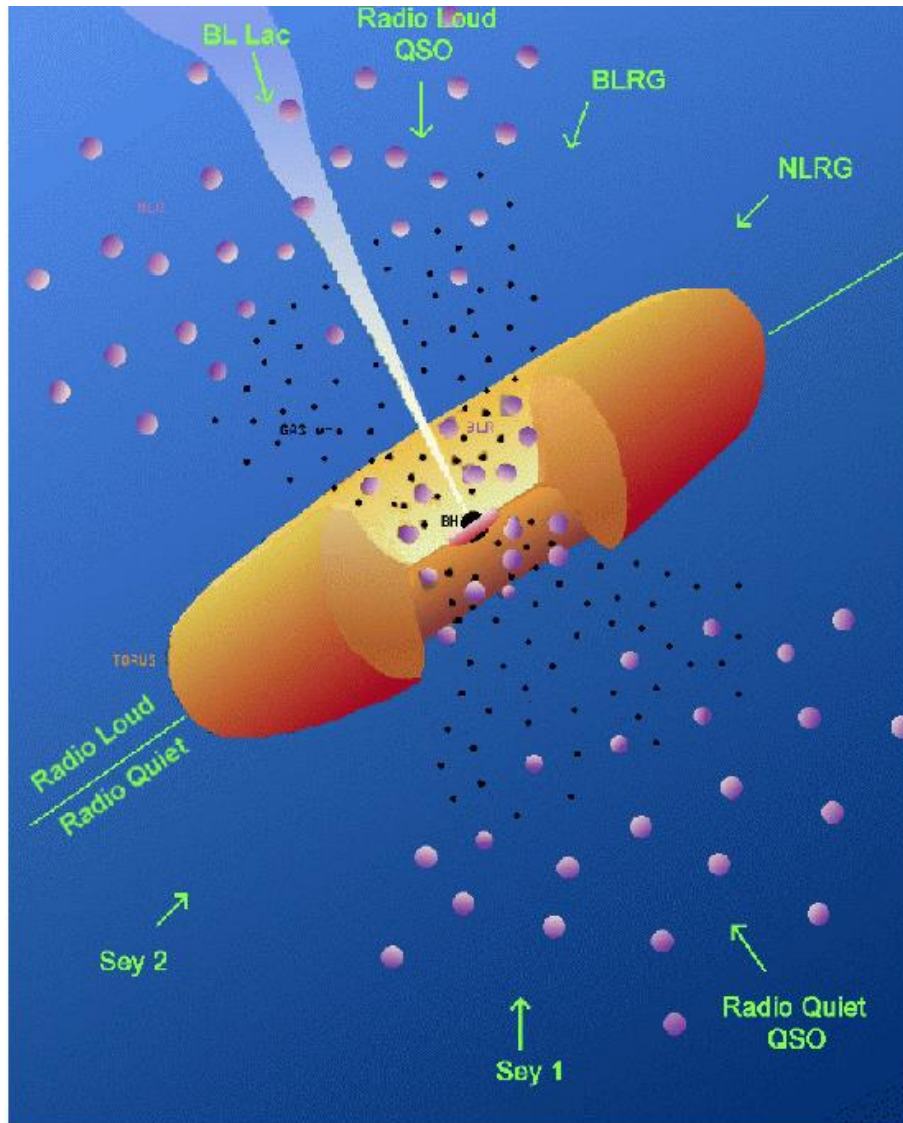
“Shock waves are frequency stratified, with highest synchrotron frequencies emitted only close to the shock front where electrons are energized. The part of the jet interior to the mm-wave core is opaque at cm wavelengths. At this point, it is not clear whether substantial emission occurs between the base of the jet and the mm-wave core.”

*Credits: Alan Marscher, 'Relativistic Jets in Active Galactic Nuclei and their relationship to the Central Engine,' Proc. of Science, VI Microquasar Workshop: Microquasars & Beyond, Societa del Casino, Como, Italy, 18-22 Sep 2006. Overlay (not to scale): 3 mm radio image of the blazar 3C454.3 (Krichbaum et al. 1999)*





# AGN: Viewing Angle Effect



## Schematic of AGN Viewing Angle

1. Down jet:  
BL Lac, Blazar
2. Small angle  
Radio loud
3. Mid-angle:  
Broad line region
4. Side view  
Narrow Line Region

Courtesy of M. Polletta, ITRSRB/CNR, Bologna, Italy  
from BeppoSas Calendar 1999; <http://www.sdc.asi.it/calendar/>



# Celestial Reference Frame: Long term stability

*GPS is not sufficient* for a long term inertial frame

**Orientation: Relative to what?**

**One must define stable (ppb) reference directions**

- GPS orbits are well modelled (ppb) over ~day time periods.

***But . . .***

- **GPS constellation node drifts over weeks. . .**



1.e18  
increase  
in range

**Solution: Change sources from range of  
GPS' s nano-Light year to  
VLBI's Giga-Light Years  
~eighteen (18) orders of magnitude!**



# Celestial Pole & Alignment of Axes

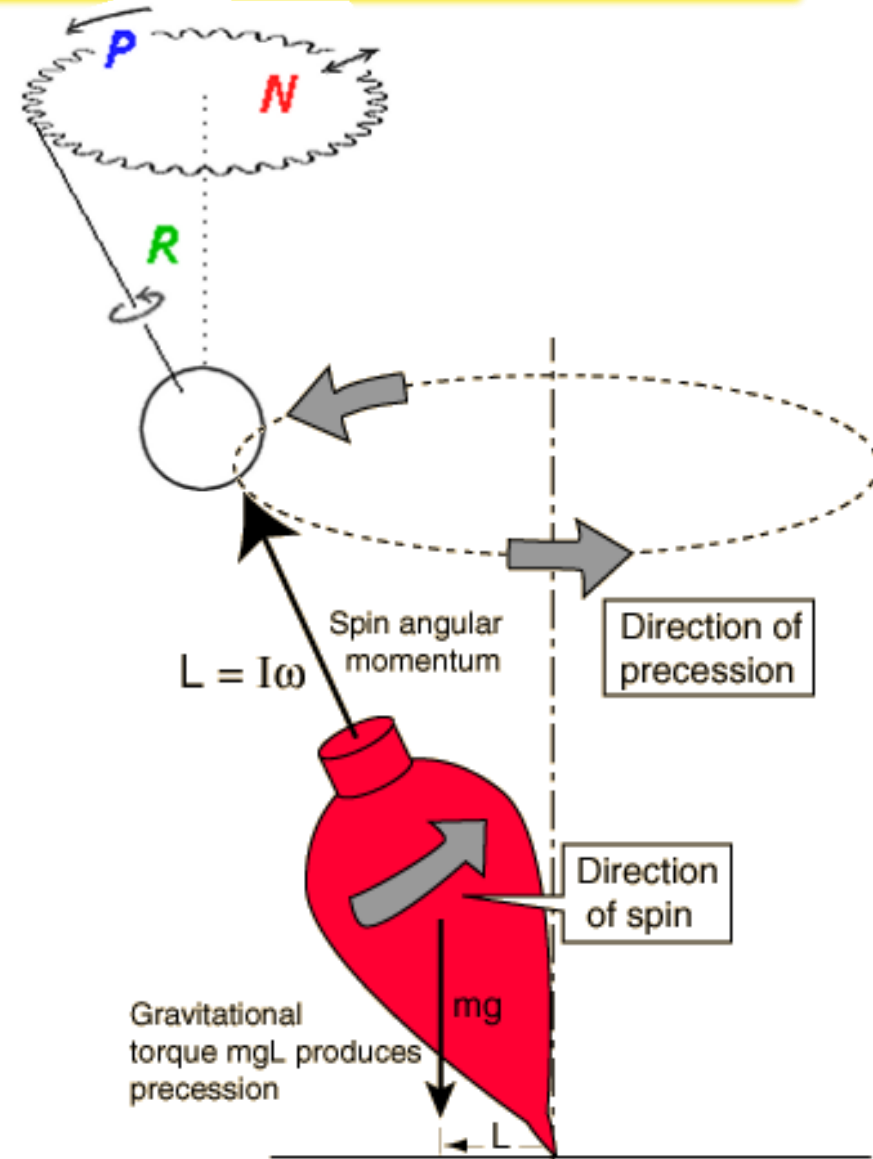
From [German Wikipedia](#),  
by [User Herbye](#).

- VLBI determines angles *between* sources
- Absolute positions only weakly determined at 10-100 mas level by tidal effects (RA, dec of Sun & Moon) and atmospheric effects (elevation)
- Orientation of axes is defined at sub-mas level by convention
- Enforced by No-Net-Rotation constraint:

$$\sum_{i=1}^N s \times Ds = 0$$

where  $s$  direction is source unit vector  
cf. [Jacobs et al, IVS, 2010](#).

<http://ivscc.gsfc.nasa.gov/publications/gm2010/jacobs2.pdf>



Credit: [www.4physics.com](http://www.4physics.com)



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## I. Concepts and Background:

- A. What is a Reference frame? Concepts, uses, desired properties
- B. Networks: The instruments used to build the frame  
ad hoc, VLBA, EVN, Global, NASA-ESA DSN, LBA, AuScope, etc.
- C. Brief history of Astrometry: The 'fixed' stars aren't so fixed.
  - 1. Precession, proper motion, nutation, parallax
  - 2. Invention of radio astronomy. VLBI's pursuit of (sub)milli-arcsecond accuracy.

## II. Celestial Frames built using VLBI

- A. Surveys: Single dish, connected array: JVAS, AT20G, and VLBI: VCS, LCS**
- B. ICRF-1, ICRF-2: The IAU moves to from optical (stars) to radio (quasars)**
- C. Higher frequency radio frames: K&Q (24 & 43GHz), X/Ka (32 GHz)**

## III. The Path to the Future:

- A. Error Budgets: a tool for allocating resources for improvement
- B. Case study: Path to Improved X/Ka (8.4/32 GHz) Frame
- C. ICRF-3: the next standard radio frame
- D. Gaia: an optical frame with high accuracy





## II.B. The Transition from Optical to Radio

- Optical to Radio transition era documented in  
Hans Walter & Ojars Sovers, *Astrometry of Fundamental Catalogues:  
The Evolution from Optical to Radio Reference Frames*, 2000  
<http://adsabs.harvard.edu/abs/2000afce.conf.....W>
- Fundamental Katalog FK5 (Fricke, 1988)  
<http://adsabs.harvard.edu/abs/1988VeARI..32....1F>  
1535 stars limited by proper motions of stars  
~150 mas regional differences from ICRF1 <http://adsabs.harvard.edu/abs/1997IAUJD...7E..24M>
- IAU called for a move to Active Galactic Nuclei (AGN)  
obtain very distant sources (redshift  $\sim 1$ ,  $\sim 5$  billion light years)  
No parallax, no proper motion
- IAU formed in 1990s a working group on  
International Celestial Reference Frame (ICRF)
- ICRF-1 adopted by the IAU as on 1998 Jan 01.  
Ma et al, AJ, 116, 516, 1998 <http://adsabs.harvard.edu/abs/1998AJ....116..516M>



## II.A. Surveys: How are sources found? Positions?

1. **Single dish surveys:** A single radio telescope sweeps the sky to search for point-like sources. Example: Parkes-MIT-NRAO 4.8 GHz (Griffith & Wright, 1993)   
 ~10 arcsec positions.

<http://www.parkes.atnf.csiro.au/observing/databases/pmn/pmnpubs.html> 1993AJ....105.1666G

2. **Connected element array surveys:**

- next step is interferometric connected arrays such as the Very Large Array or ATCA
- Positions improved to 10s of milli-arcsec

- **North:** Jodrell Bank VLA Survey (JVAS) (Patnaik et al, MNRAS, 1992)

<http://adsabs.harvard.edu/abs/1992MNRAS.254..655P>



<http://www.vla.nrao.edu/>

- **South:** ATCA 20-GHz (AT20G), 5890 sources, Southern hemisphere (Murphy et al, MNRAS, 2010)

<http://www.atnf.csiro.au/research/AT20G> <http://adsabs.harvard.edu/abs/2010MNRAS.402.2403M>

3. **Final Survey stage:** VLBI gets ~milli-arcsec positions e.g

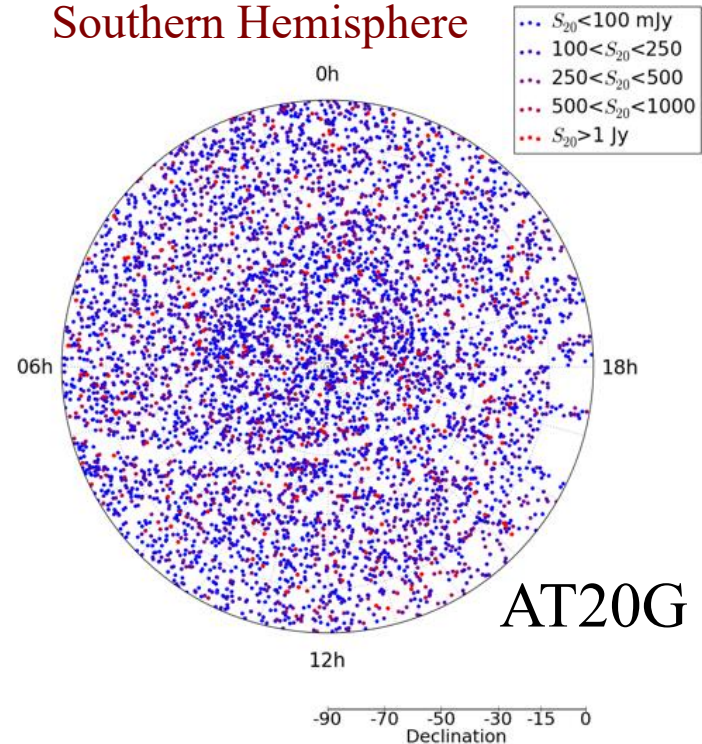
- **North:** VLBA Calibrator Survey (Beasley et al, ApJS, 2002)

<http://adsabs.harvard.edu/abs/2002ApJS..141...13B>

- **South:** LBA Calibrator Survey, (Petrov et al, MNRAS, 2011)

<http://arxiv.org/abs/1012.2607> <http://adsabs.harvard.edu/abs/2011MNRAS.414.2528P>

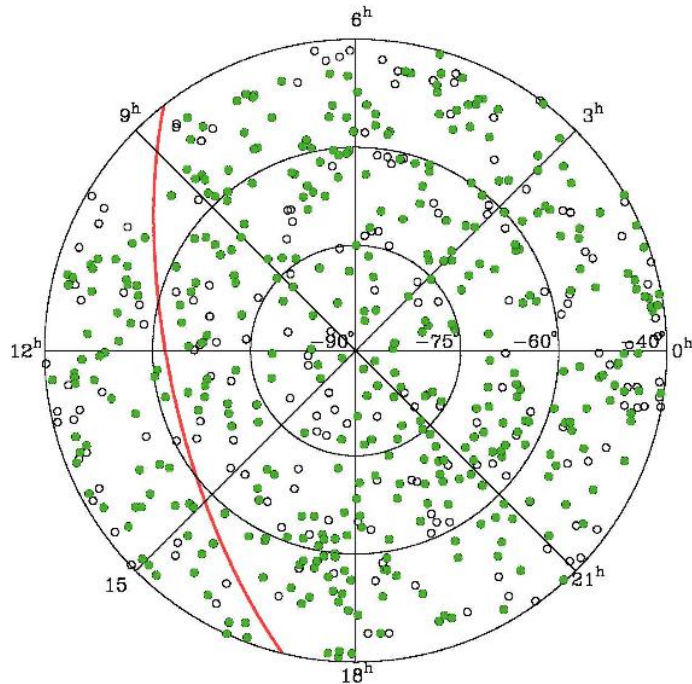
### Southern Hemisphere



<http://www.narrabri.atnf.csiro.au/public/>



## II.A. Surveys: milli-arcsec VLBI surveys



South:

LBA Cal Survey1:

~1 mas accuracy

view from south pole

<http://arxiv.org/pdf/1012.2607v2.pdf>

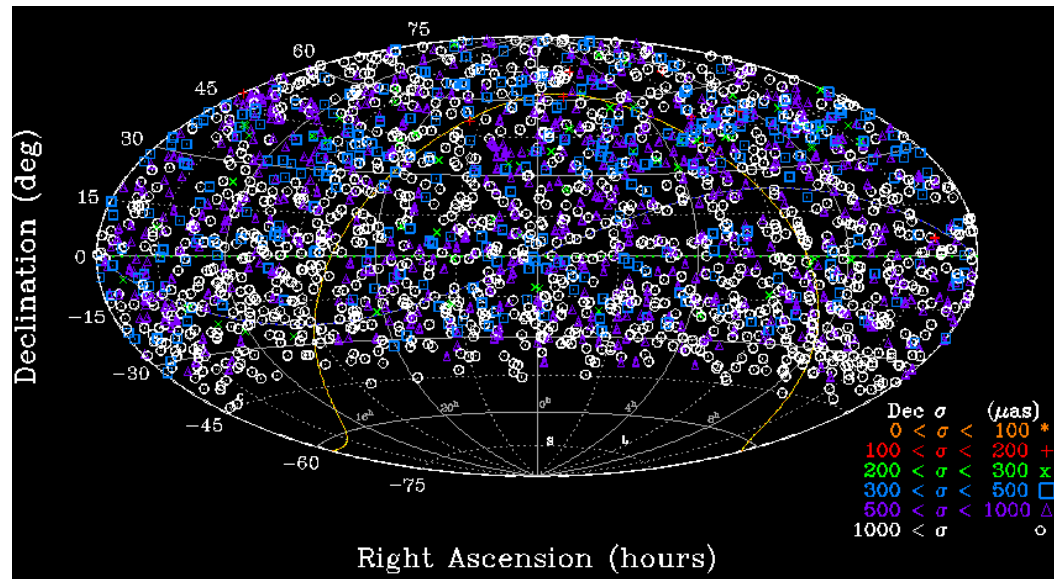


Figure credit: C.S. Jacobs

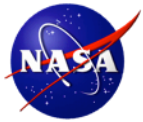
North:

VLBA Calibrator Survey

~2200 sources, ~1 mas

Hammer-Aitoff Projection

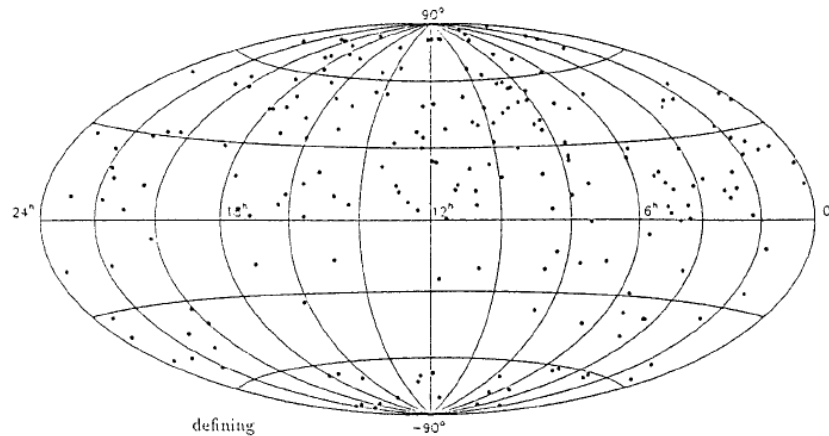
<http://adsabs.harvard.edu/abs/2002ApJS..141...13B>



# 1st International Celestial Reference Frame

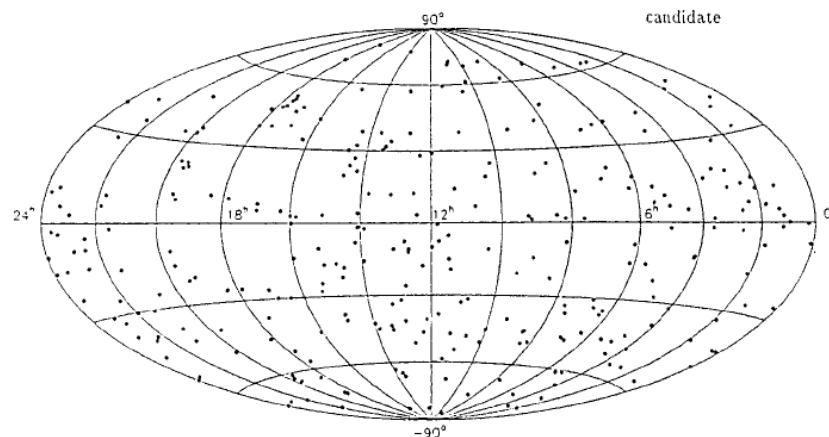
- ICRF-1 adopted by the IAU as on 1998 Jan 01.

Ma et al, AJ, 116, 516, 1998 <http://adsabs.harvard.edu/abs/1998AJ....116..516M>



212 “Defining” sources  
which define the orientation  
of the frame’s axes.

**Weak in the south.**



“Candidate” sources (left)  
Plus a few “other” sources  
For a total of 608 sources.





# Current Status of Celestial Reference Frames at radio wavelengths:

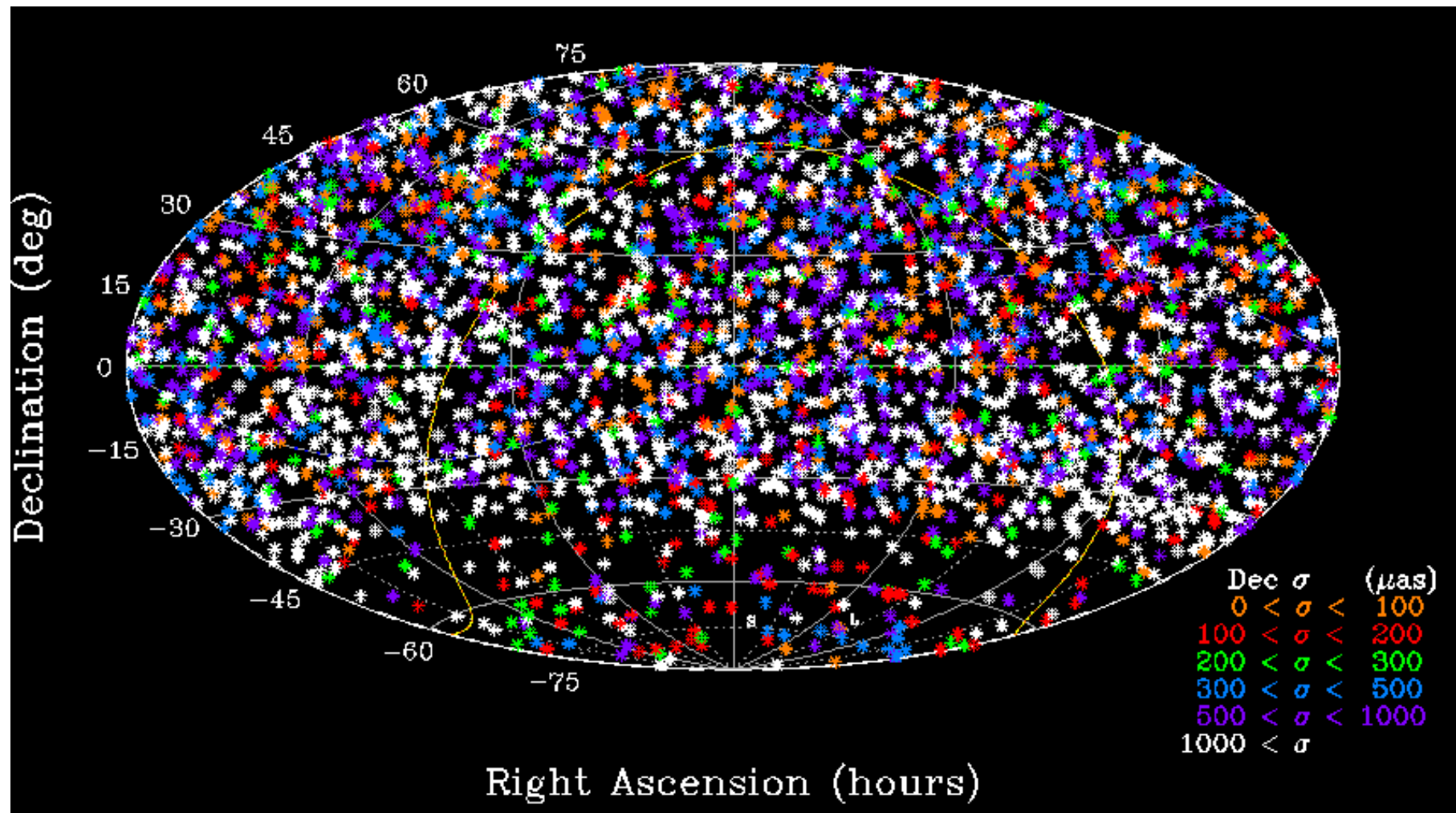
**S/X ICRF2:** 3.6cm, 8 GHz

**K-band:** 1.2cm, 24 GHz

**X/Ka-band:** 9mm, 32 GHz



# ICRF-2 S/X 3.6cm: 3414 sources



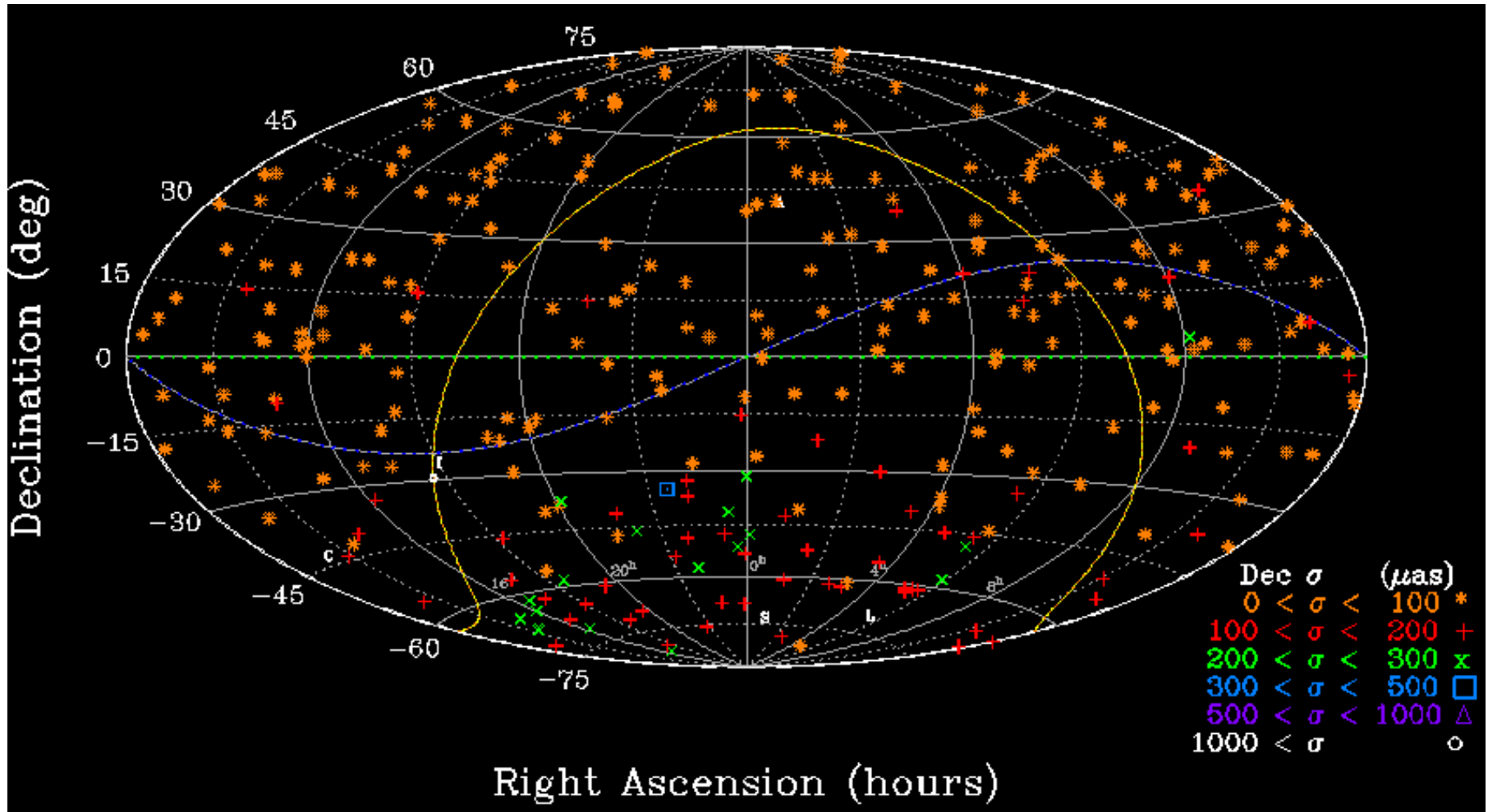
40  $\mu$ as floor.  $\sim 1200$  obj. well observed,  $\sim 2000$  survey session only

Credit: Ma et al, eds. Fey, Gordon, Jacobs, IERS Tech. Note 35, Germany, 2009

<http://adsabs.harvard.edu/abs/2009ITN....35....1M>



# ICRF2 S/X 3.6cm: 295 Defining sources



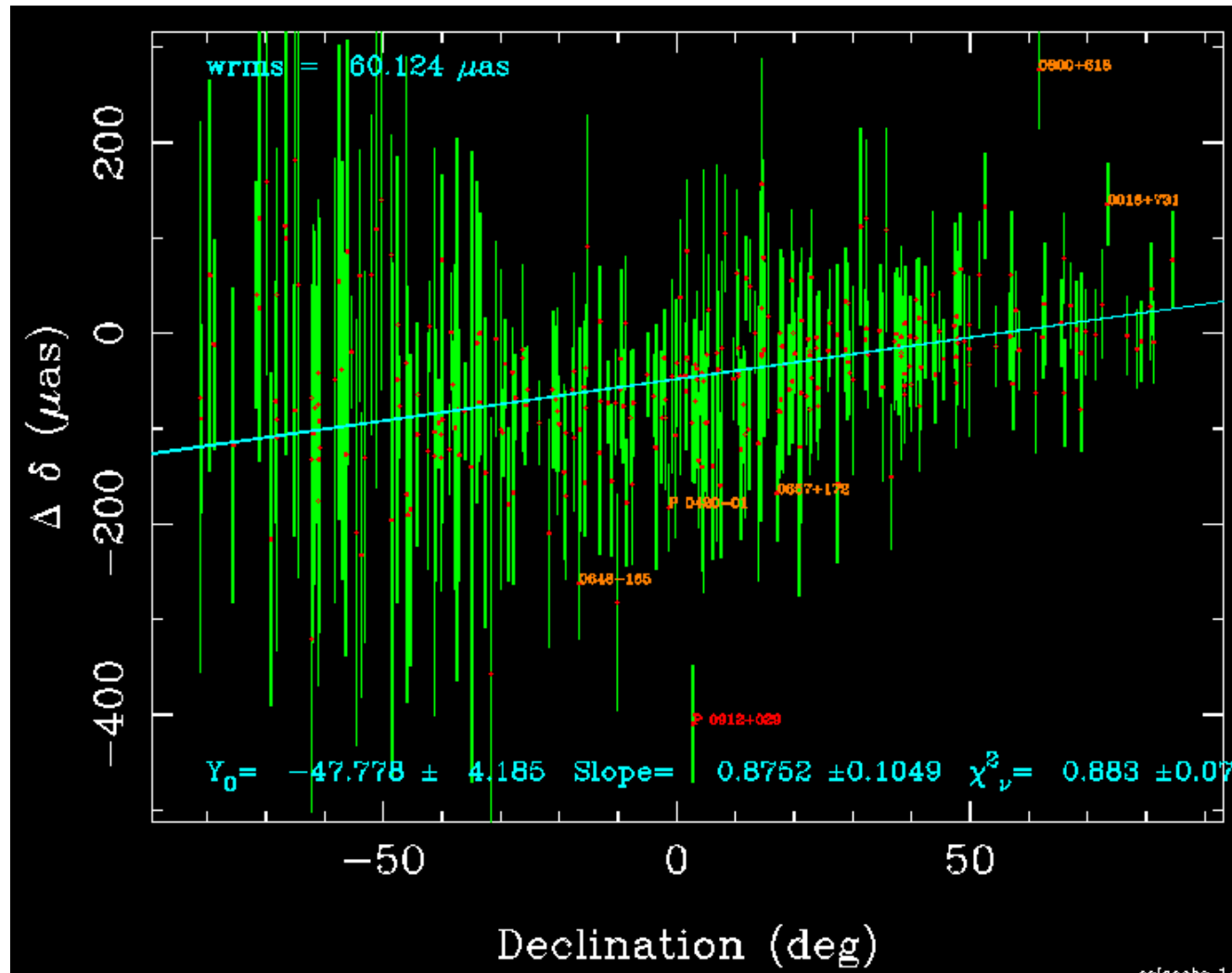
295 “best” sources Define the orientation of the axes. **Weak in the South**

Credit: Ma et al, eds. Fey, Gordon, Jacobs, IERS Tech. Note 35, Germany, 2009

<http://adsabs.harvard.edu/abs/2009ITN....35....1M>



# S/X zonal errors: ICRF2 vs. Recent S/X



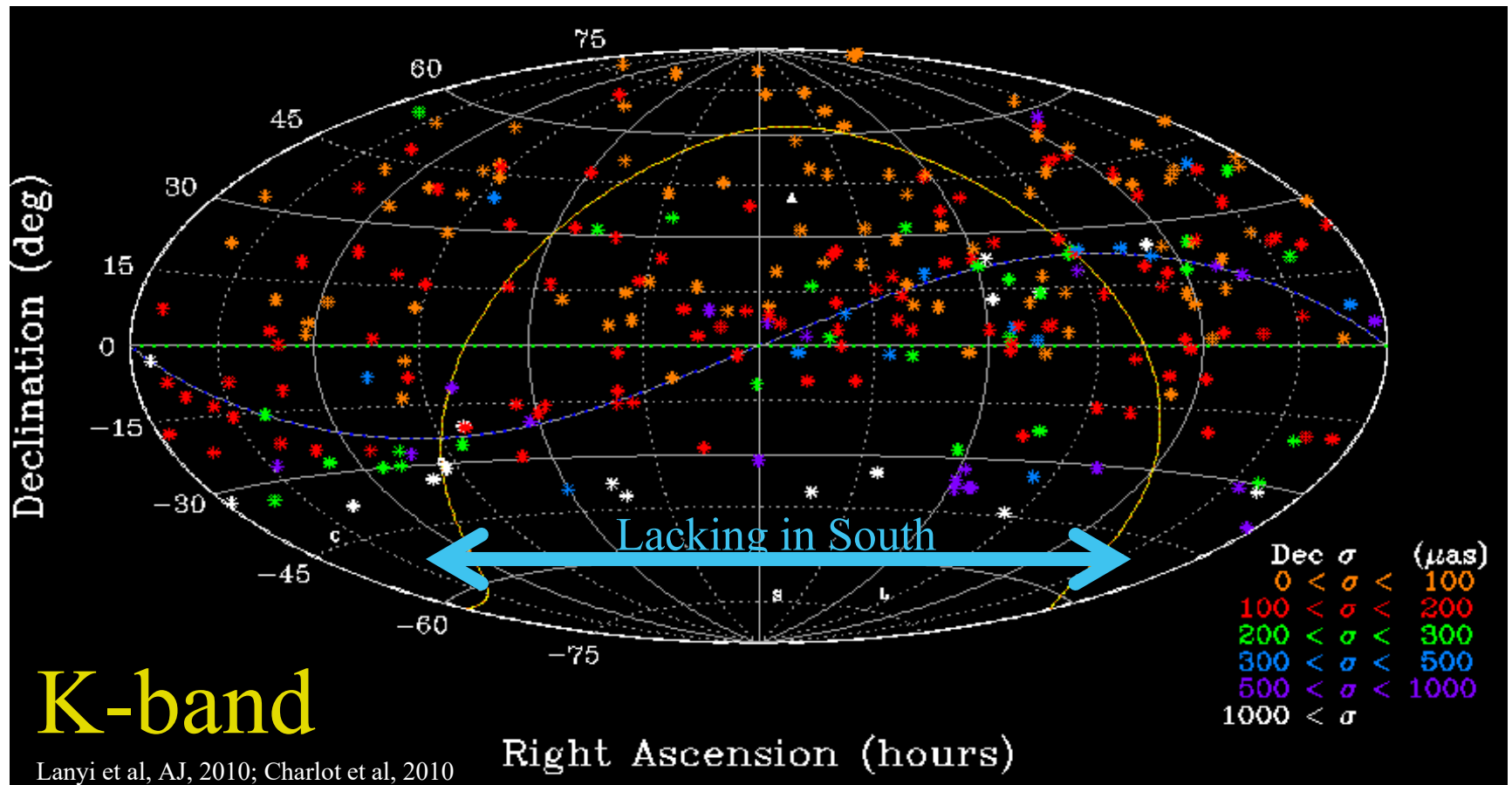
Credit:  
Gordon et al, GSFC,  
private .comm., 2014

GSFC-2014bp3 – ICRF2 Definings: 0.5 ppb zonal error in Declination





# K-band (24 GHz) CRF: 275 sources



Work stopped c. 2010.

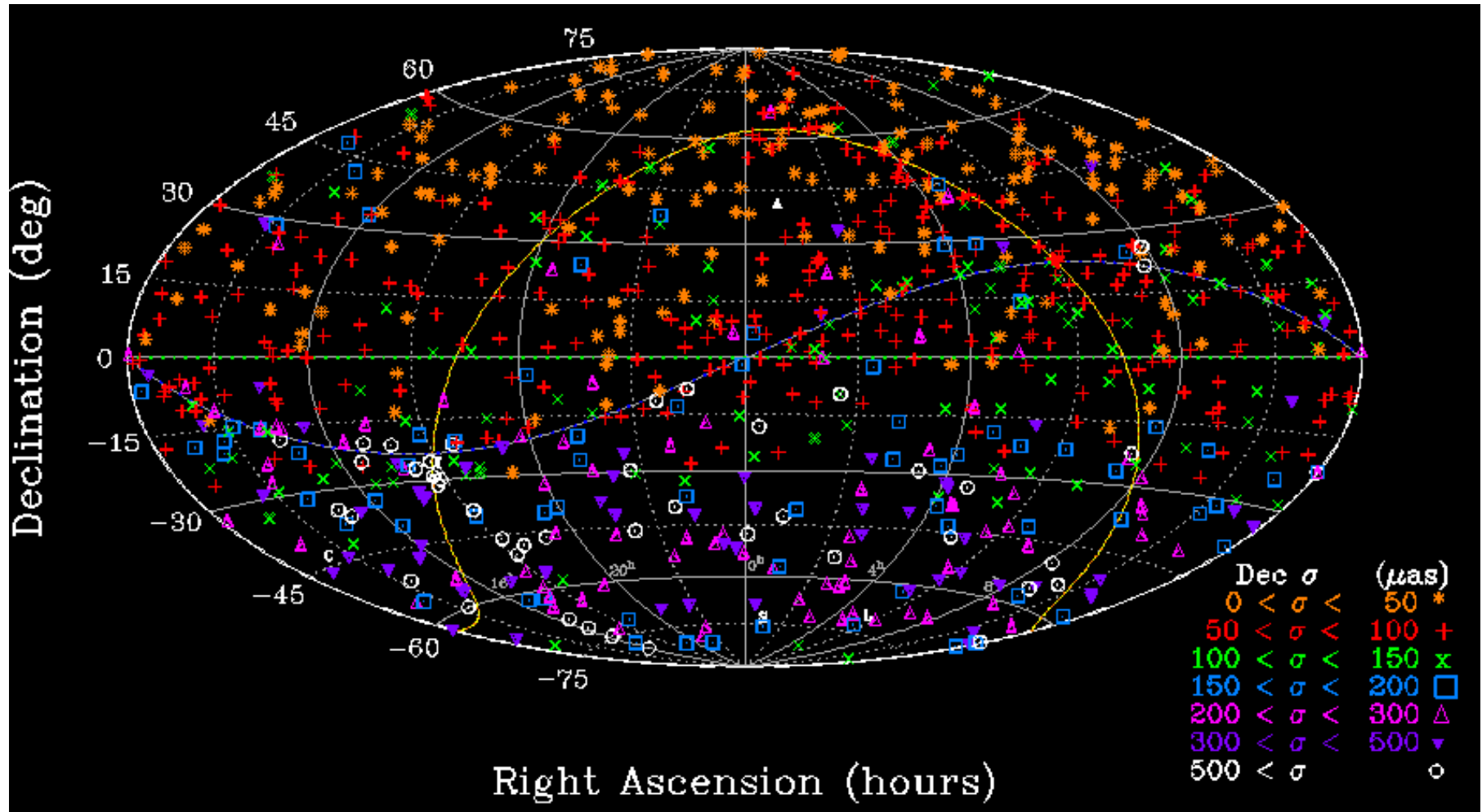
Resumed 2013. First southern K-band fringes: Hobart-HartRAO (23 Aug 2013)

VLBA work resumed 2016 (project BJ083). Extended in 2017 (UD001)



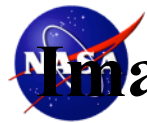


# K-band (24 GHz) CRF: 826 sources

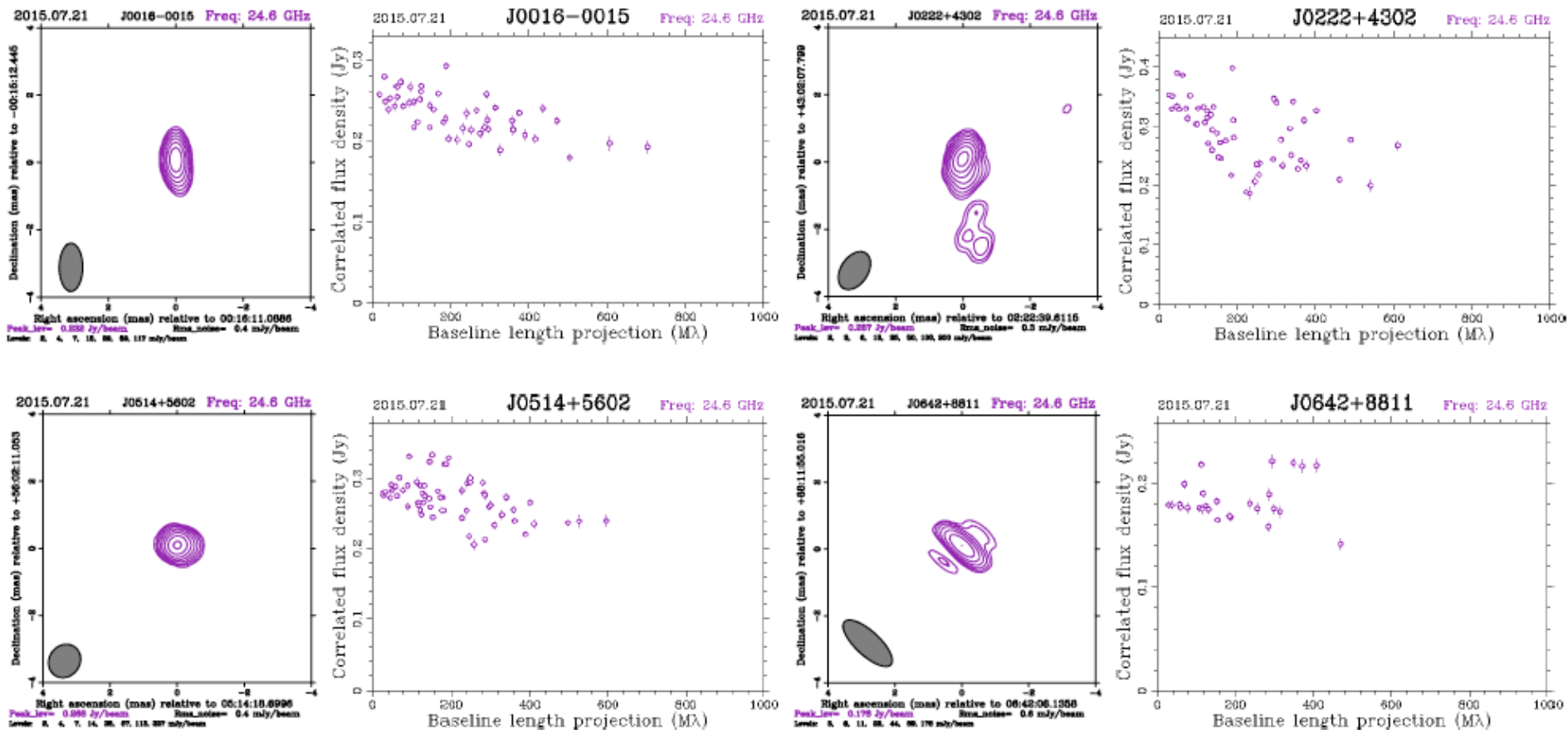


VLBA 35 sessions @2Gbps to densify the north (*de Witt et al, EVGA, 2017*)

Hart-Hobart (Tianma): 15 sessions. Archive (*Lanyi et al, 2010, Petrov et al, 2006*).



# Imaging: VLBA at 24 GHz (1.2cm) (de Witt et al, 2016)



K-band (24 GHz) imaging shows VLBI sources are compact on millarcsec scales.  
Data for 500+ sources acquired. Processing limited by available analyst resources.  
Imaging will be prioritized as comparison outliers pinpoint sources of interest





# I.B. Observing Networks

## VLBA

S/X VCS catalog

K, Q catalogs

25-meter dishes

10 stations

Baselines up to  
8000 km

No southern  
stations



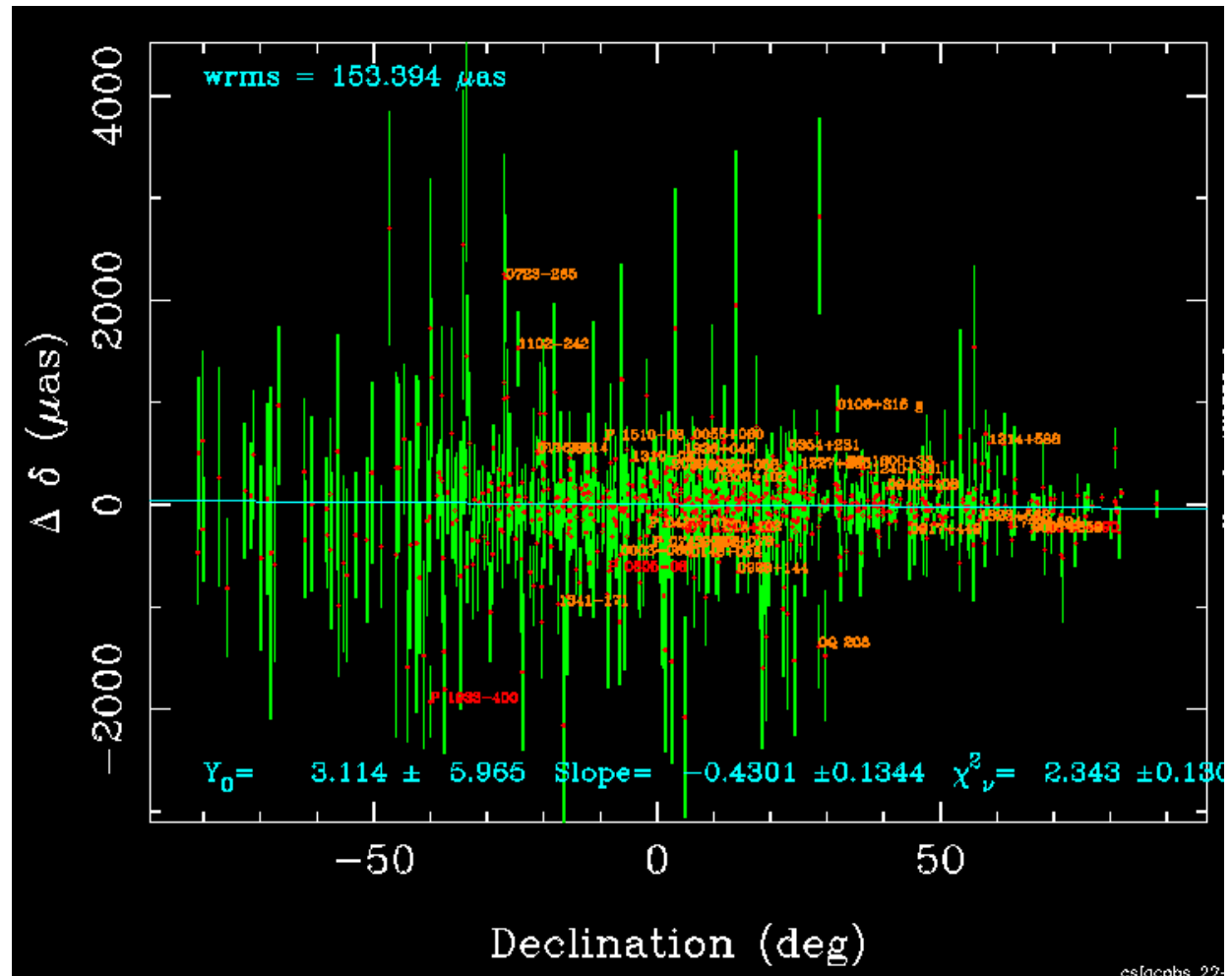
Very Large Baseline Array <http://www.vlba.nrao.edu/>



*Added baseline  
Hart-Hobart  
in south*

$\Delta$ Dec vs. Dec  
Tilt now an order  
of magnitude  
Improved!!!

Tilt of  
-43  $\mu$ as over  
100 deg span

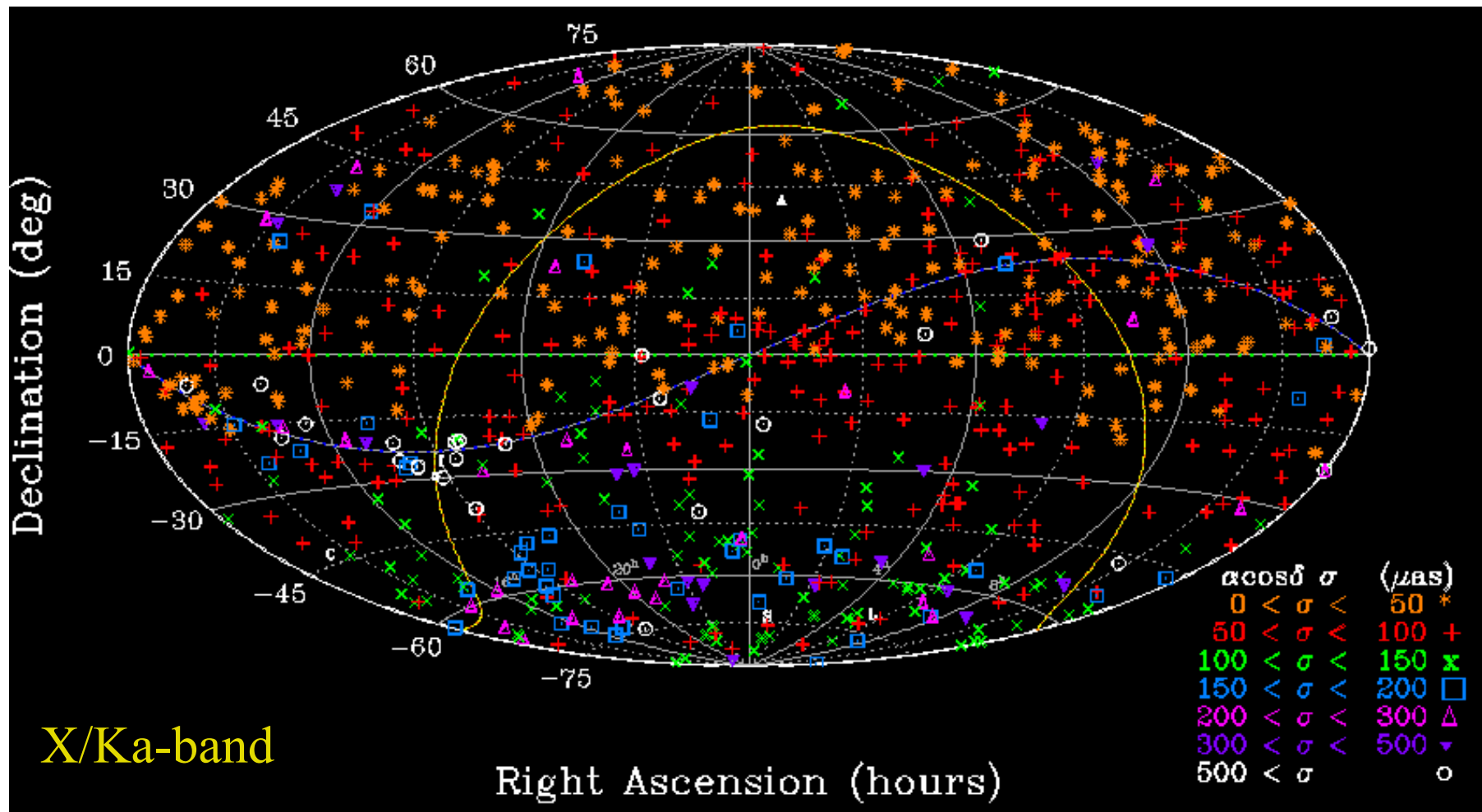


### K (2017 Mar 20) Declinations vs. S/X (2016 Dec 20)

*Credit: K(1.2cm): Gordon, priv. comm 20 Mar 2017*  
*S/X: Gordon 2016 Dec 20*



# X/Ka RA results (NASA-ESA): 681 Sources

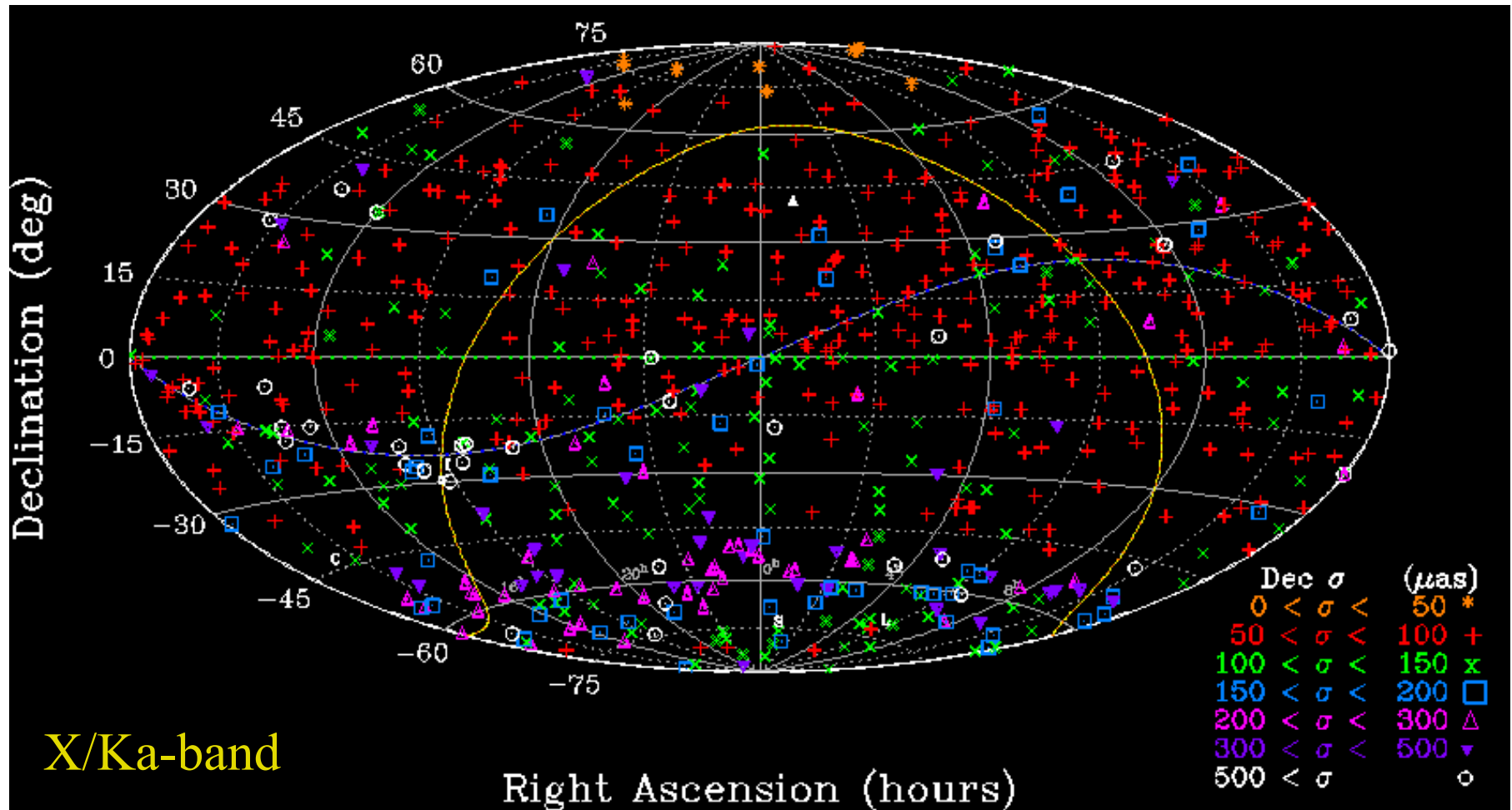


Goldstone, CA to Madrid & Australia + **Malargüe to Canberra, Goldstone, Madrid**.  
 134 sources in south cap (dec<-45); **27 ICRF2 Defining**; 2/3 of south cap non-ICRF2

Credit: Jacobs et al, IAU330, 2017; Garcia-Miro et al, EVN, 2014



# X/Ka Dec results (NASA-ESA): 674 Sources



DSN: Goldstone, CA to Madrid & Canberra  
+ ESA baselines: Malargüe to Canberra, Goldstone, Madrid

Credit: Jacobs et al, IAU 330, 2017; Garcia-Miro et al, EVN Symposium, 2014

Jacobs et al, ISSFD, Pasadena, 2012 <http://adsabs.harvard.edu/abs/2012sfed.confE...1J>



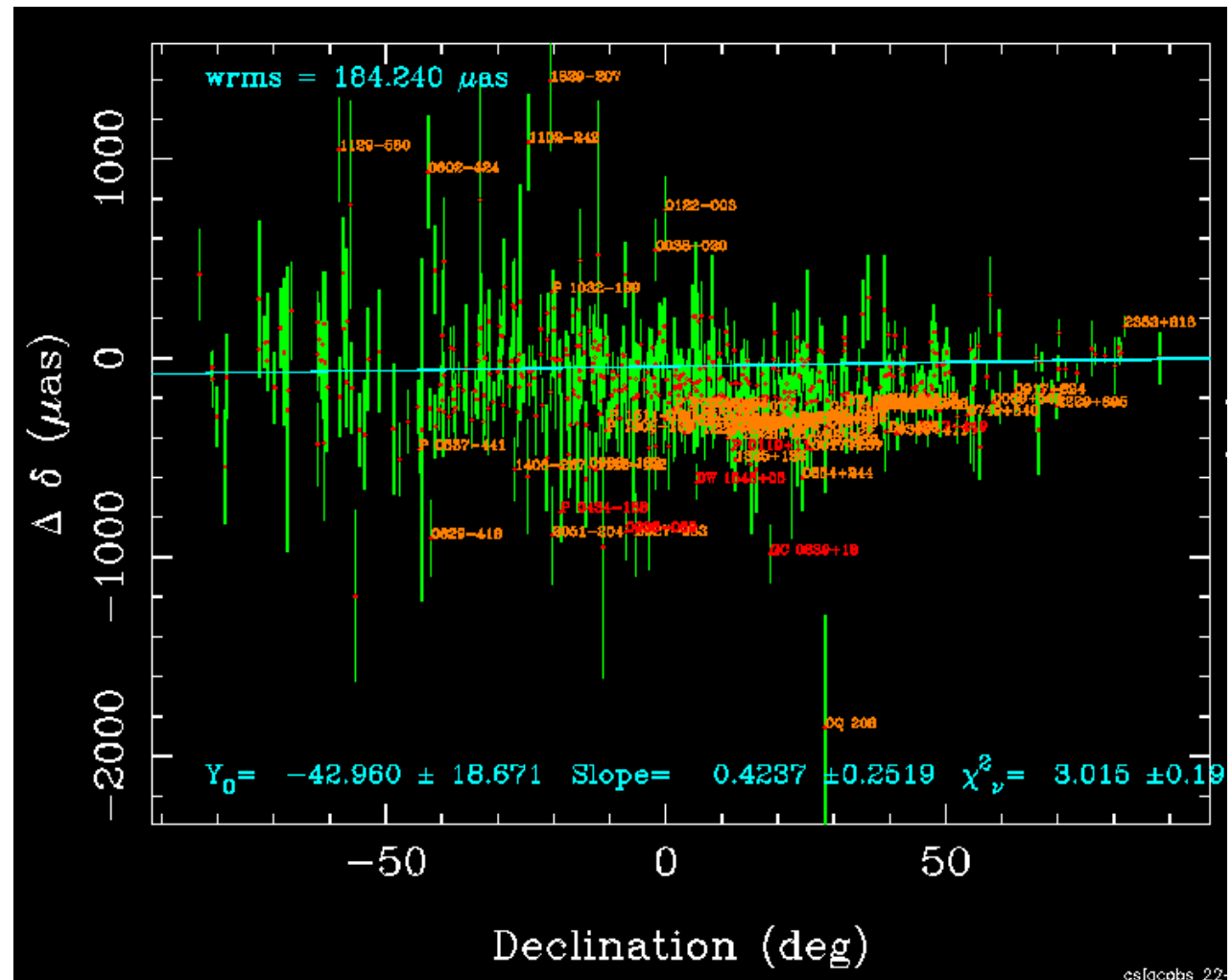


# 9mm (X/Ka) vs. 3.6cm (S/X)

Dual-band ion  
Calibrations  
*and*  
Station in south

Leads to better  
 $\Delta$ Dec vs. Dec  
Zonal stability:

42  $\pm$  25  $\mu$ as tilt  
over 100 degrees



**X/Ka(9mm) Dec. vs. S/X (3.6cm)**

*X/Ka, Garcia-Miro et al, EVN, 2014, Jacobs et al, 2016,  
S/X: Gordon et al, private comm., GSFC, 20 Dec 2016*



Figure 1 is a scatter plot showing the relationship between Declination (deg) on the x-axis and  $\Delta \alpha \cos \delta$  (mas) on the y-axis. The x-axis ranges from -50 to 100, and the y-axis ranges from -500 to 1000. Data points are represented by red dots with vertical error bars. A blue linear regression line is fitted to the data. The plot includes several labeled points with their corresponding P values and coordinates. The overall rms is 158.132 mas. The y-intercept  $Y_0$  is  $-6.504 \pm 1.425$ , the slope is  $1.1188 \pm 0.1896$ , and the chi-squared value is  $\chi^2_\nu = 3.092 \pm 0.196$ .

*X/Ka, Garcia-Miro et al, EVN, 2014, Jacobs et al, 2016,  
S/X: Gordon et al, private comm., GSFC, Dec 2016*



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## III. The Path to the Future:

- A. Error Budgets: a tool for allocating resources for improvement
- B. Next-generation geodetic VLBI: Ultra-wide 2-14 GHz
- B. Case study: Path to Improved X/Ka (8.4/32 GHz) Frame
- C. ICRF-3: the next standard radio frame

### **D. Gaia: the return of optical**



## III.D. Gaia Optical Frame

---

### Gaia-Optical vs. VLBI-radio:

**Celestial Frame tie  
and  
Accuracy Verification**





# Gaia frame tie and accuracy verification

## Gaia: $10^9$ stars

- 500,000 quasars  $V < 20$   
20,000 quasars  $V < 18$
- radio loud 30-300+ mJy  
and optically bright:  $V < 18$   
~2000 quasars
- Accuracy  
70  $\mu\text{as}$  @  $V=18$   
25  $\mu\text{as}$  @  $V=16$

## Gaia References:

Lindgren et al, IAU 248, 2008

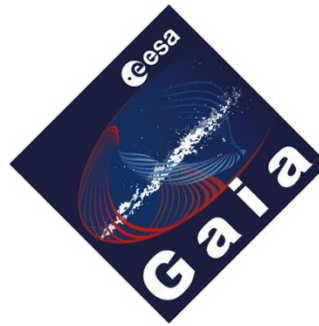
<http://adsabs.harvard.edu/abs/2008IAUS..248..217L>

Mignard, IAU, JD-7, 2012

[http://referencesystems.info/uploads/3/0/3/0/3030024/fmignard\\_iau\\_jd7\\_s3.pdf](http://referencesystems.info/uploads/3/0/3/0/3030024/fmignard_iau_jd7_s3.pdf)

<http://adsabs.harvard.edu/abs/2012IAUJD...7E..27M>

- S/X Frame Tie Strategy:  
Bring new optically bright quasars  
into the S/X radio frame  
use sources with S/X fluxes 30-100 mJy  
(Bourda et al, EVN, Bordeaux, 2012)



Launched Dec 2013  
(*Francois Mignard*)

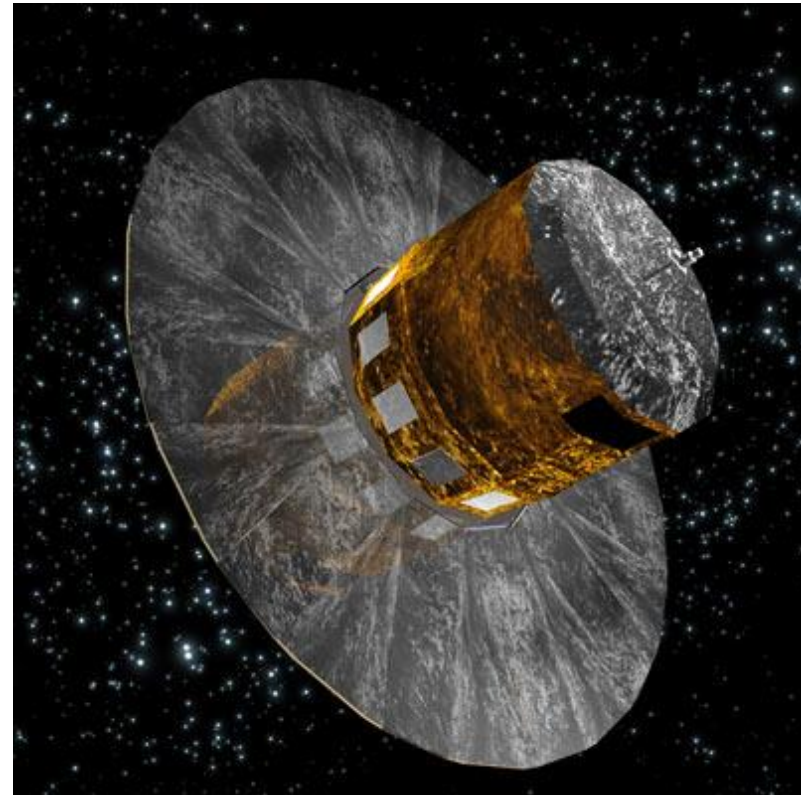
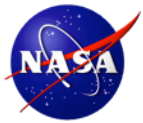


Figure credit: [http://www.esa.int/esaSC/120377\\_index\\_1\\_m.html#subhead7](http://www.esa.int/esaSC/120377_index_1_m.html#subhead7)

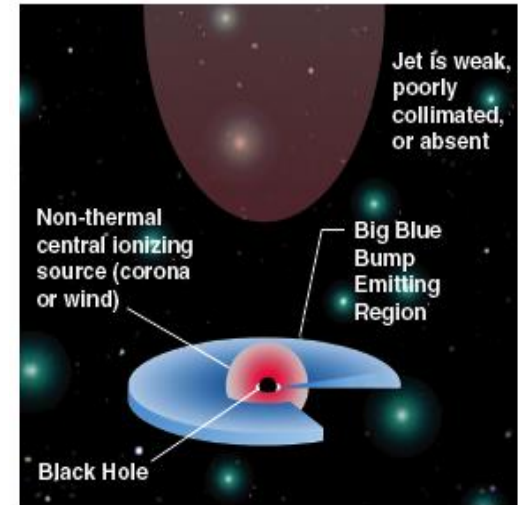


# Optical vs. Radio positions

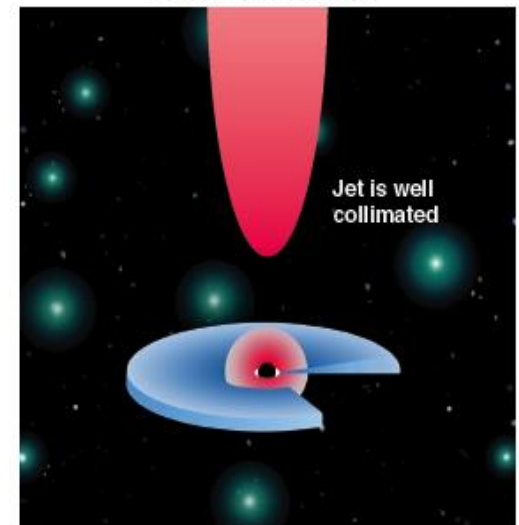
Positions differences from:

- Astrophysics of emission centroids
  - radio: synchrotron from jet
  - optical: synchrotron from jet?  
non-thermal ionization from corona?  
big blue bump from accretion disk?
- Instrumental errors both radio & optical
- Analysis errors

Radio-quiet Quasar



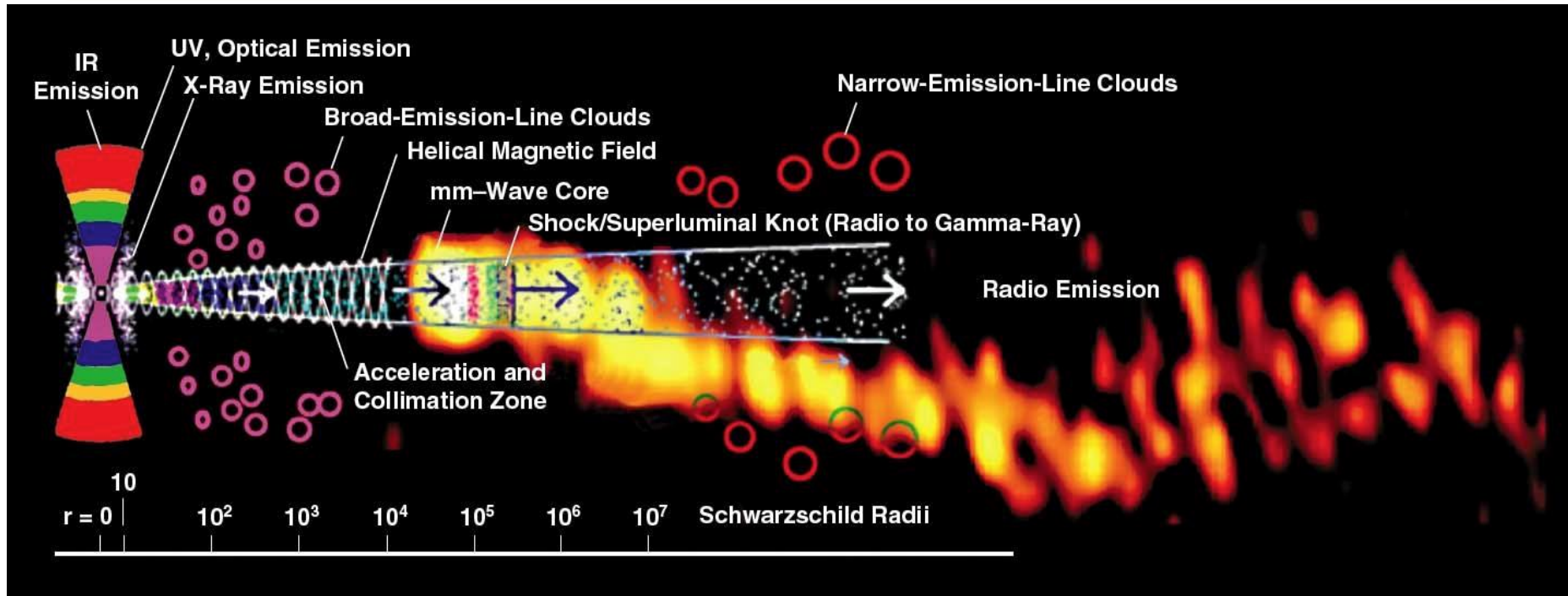
Radio-loud Quasar



Credit: Wehrle et al, *pas Science*, Socorro, 2009  
<http://adsabs.harvard.edu/abs/2009astro2010S.310W>



# 9mm vs. 3.6cm? Core shift & structure



Credit: A. Marscher, Proc. Sci., Italy, 2006.  
Overlay image: Krichbaum, et al, IRAM, 1999.  
Montage: Wehrle et al, ASTRO-2010, no. 310.

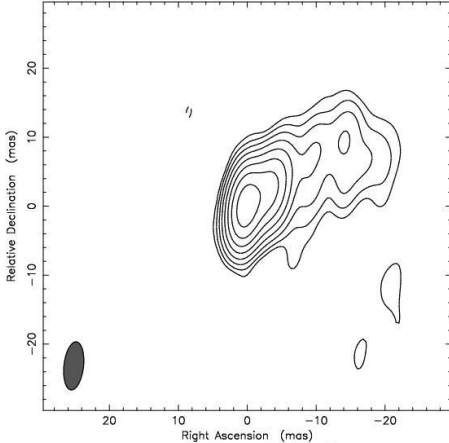
## Positions differences from 'core shift'

- wavelength dependent shift in radio centroid.
- *3.6cm to 9mm core shift:*
  - 100  $\mu$ s in phase delay centroid?
  - <<100  $\mu$ s in group delay centroid? (Porcas, AA, 505, 1, 2009)
- shorter wavelength closer to Black hole and Optical: 9mm X/Ka better
- Event Horizon Telescope (230 GHz) probing  $\sim 10$  Schwarzschild radii (Doelman et al)



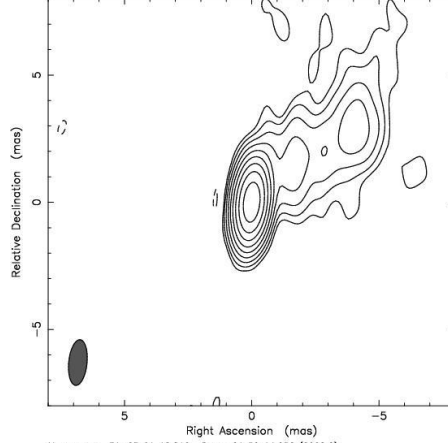
# Source Structure vs. Wavelength

Clean RR map. Array: BFGGKLMNNOOPSTWKW  
0458-020 at 2.302 GHz 2002 Jan 16



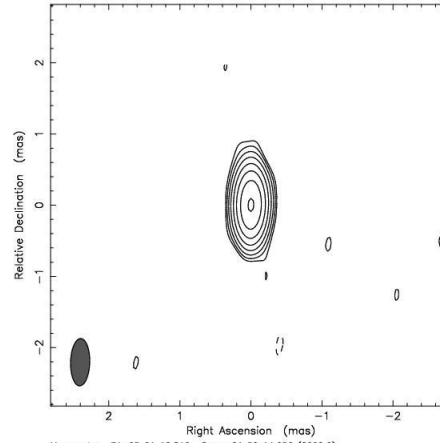
Map center: RA: 05 01 12.810, Dec: -01 59 14.256 (2000.0)  
Map peak: 0.415 Jy/beam  
Contours: 0.00195 Jy/beam x (-1 1 2 4 8 16 32 64)  
Contours: 128 J  
Beam FWHM: 7.01 x 2.85 (mas) at -6.43°

Clean RR map. Array: BFGGKLMNNOOPSTWKW  
0458-020 at 8.646 GHz 2002 Jan 16



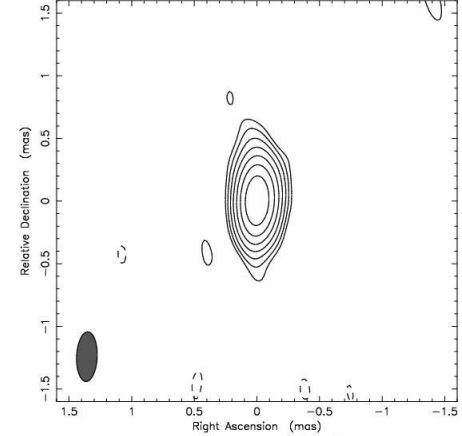
Map center: RA: 05 01 12.810, Dec: -01 59 14.256 (2000.0)  
Map peak: 0.727 Jy/beam  
Contours: 0.00168 Jy/beam x (-1 1 2 4 8 16 32 64)  
Contours: 128 Jy/beam  
Beam FWHM: 1.8 x 0.719 (mas) at -5.72°

Clean RR map. Array: BFHKLMNOPS  
0458-020 at 24.439 GHz 2002 May 15



Map center: RA: 05 01 12.810, Dec: -01 59 14.256 (2000.0)  
Map peak: 0.896 Jy/beam  
Contours: 0.00664 Jy/beam x (-1 1 2 4 8 16 32 64)  
Contours: 128 J  
Beam FWHM: 0.665 x 0.269 (mas) at -1.46°

Clean RR map. Array: BFHKLMNOPS  
0458-020 at 43.139 GHz 2002 May 15



Map center: RA: 05 01 12.810, Dec: -01 59 14.256 (2000.0)  
Map peak: 0.664 Jy/beam  
Contours: 0.00533 Jy/beam x (-1 1 2 4 8 16 32 64)  
Contours: 128 J  
Beam FWHM: 0.396 x 0.164 (mas) at -2.32°

S-band  
2.3 GHz  
13.6cm

X-band  
8.6 GHz  
3.6cm

K-band  
24 GHz  
1.2cm

Q-band  
43 GHz  
0.7cm



Ka-band  
32 GHz  
0.9cm

The sources become better ----->

Image credits: Pushkarev & Kovalev A&A, 544, 2012 (SX); P. Charlot et al, AJ, 139, 5, 2010 (K)



# Optical brightness of X/Ka sources

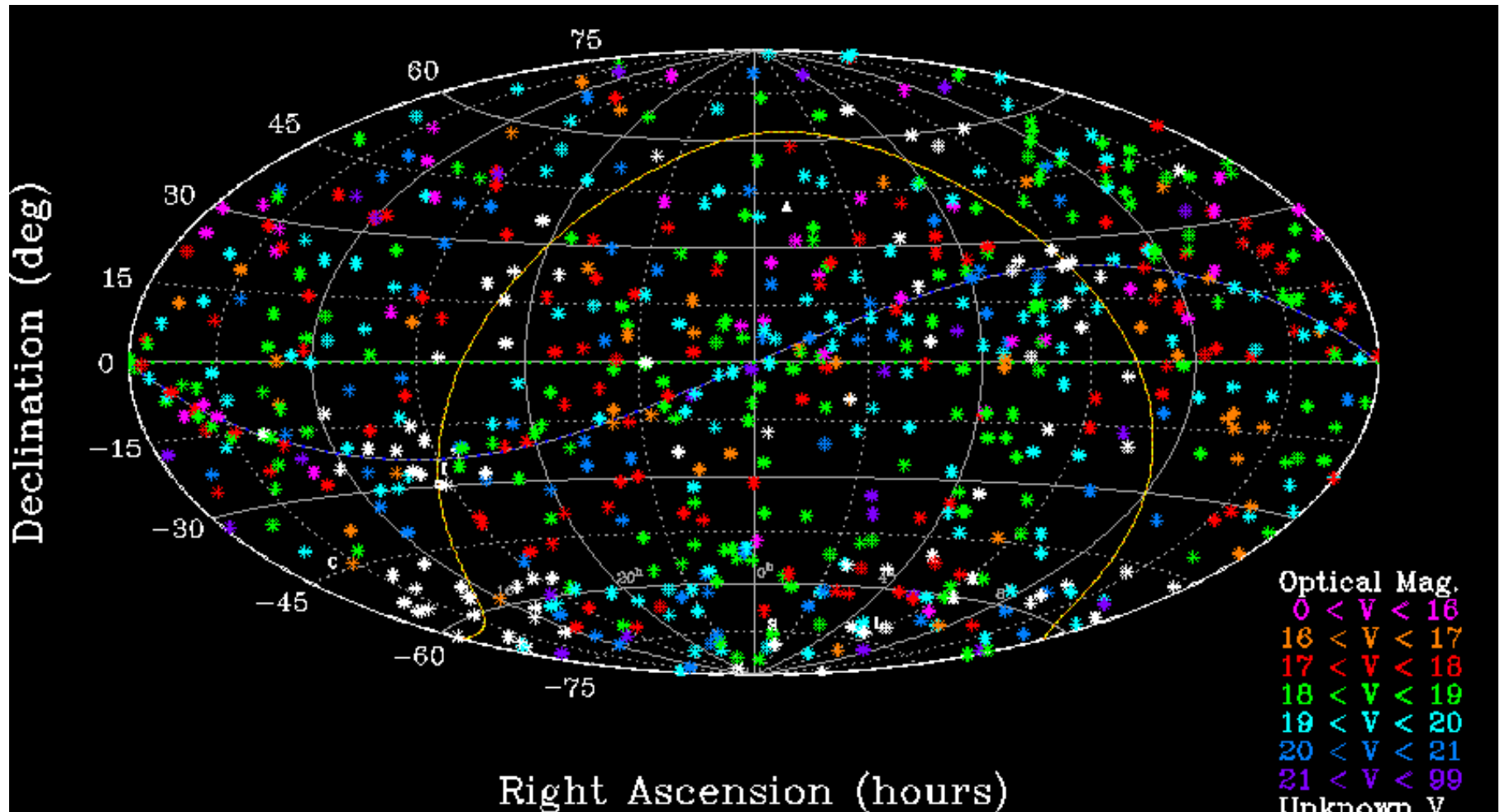
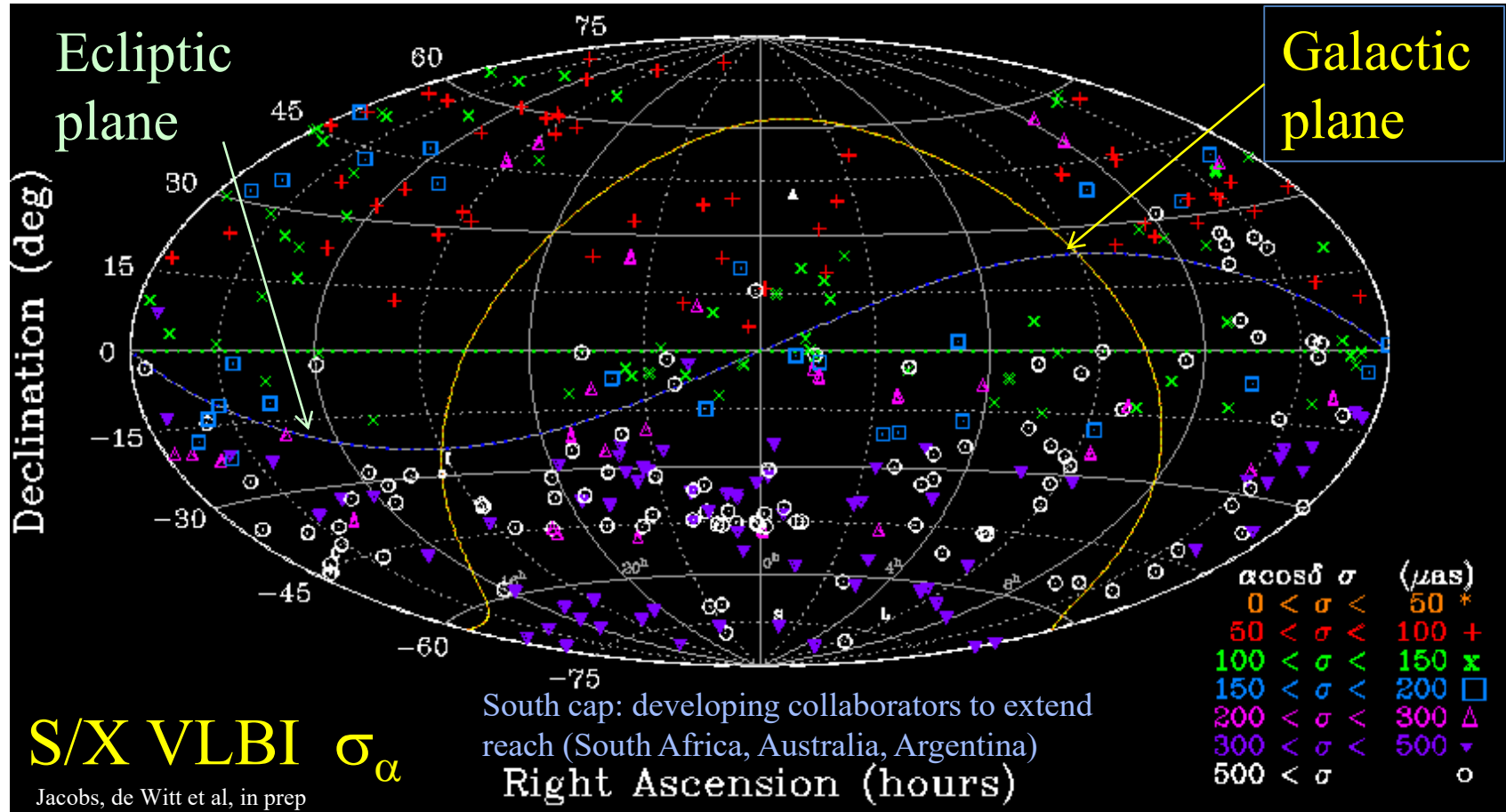


Figure credit: Garcia-Miro et al, EVN, 2014

Median optical magnitude  $V_{\text{med}} = 18.6$  magnitude (some obj. no data)  
 ~200 of 674 objects optically bright by Gaia standard ( $V < 18$ )

# Adding optically bright sources to radio

Credit: G. Bourda et al, 2014; Garcia-Miro, EVN, 2014; Jacobs et al, 2016

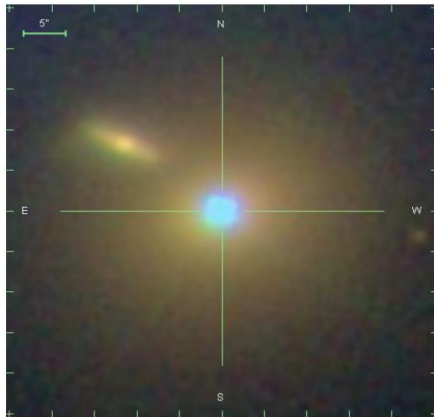


- S/X (3.6cm): Adding ~300 optically bright sources to radio frame
- Southern hemisphere additions from HartRAO-Hobart
- XKa (9mm) will only see a fraction of these due to sensitivity limits

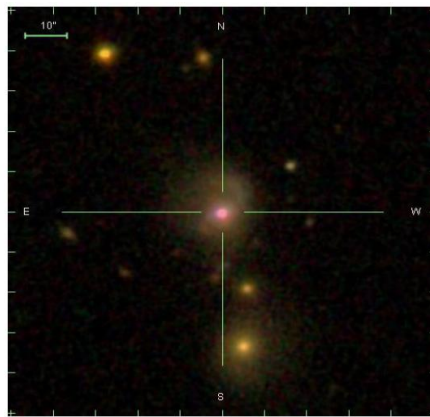


# Optical vs. Radio systematics offsets

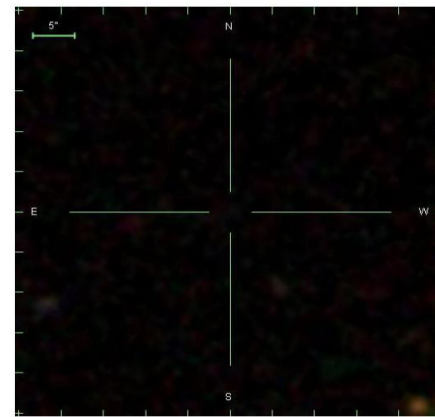
Credit: SDSS



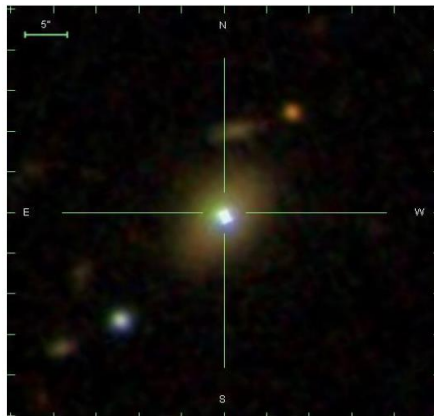
1101+384



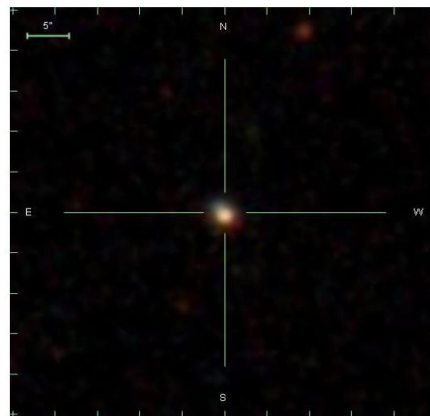
0007+106



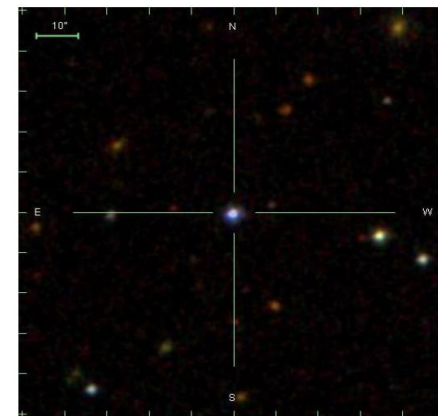
0920+390



1418+546



1514+192



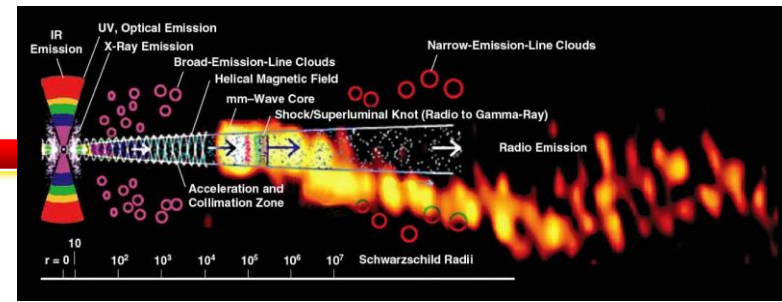
1546+027

- Optical structure: The host galaxy may not be centered on the AGN or may be asymmetric.
- Optical systematics: fraction of milliarcsecond optical centroid offset? (Petrov & Kovalev, IAU 330, 2017).
- Optical imaging generally 10s of milliarcsecond. In general, no sub-mas optical imaging.



# Frame Tie Comparisons

Tying Optical and Radio Celestial Frames  
Systematics to be flushed out via  
Inter-comparison of multiple high  
precision frames.

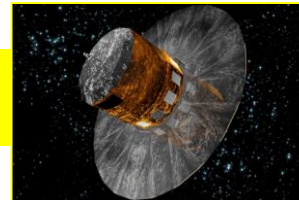


Credit: Marscher+, Krichbaum+

Gaia Optical



ALMA  
350 GHz



XKa  
32 GHz

S/X 8 GHz

K 24 GHz



## Systematics:

Gaia: 60 mas beam sees  
Host galaxy, foreground stars, etc.

ALMA: pilot obs bright end  $\sim 5^{\text{mag}}$   
Waiting on 10km+ configurations

VLBI: All bands need more  
southern data

S/X: Source structure

K: Ionosphere

XKa: Argentina baselines  
under-observed



# Gaia Data Release 1 optical vs. VLBI radio: 0.5 mas

Credit: SDSS

	SX-band 8 GHz 3.6cm	K-band 24 GHz 1.2 cm	XKa-band 32 GHz 0.9 cm
# Observations	12 million	0.25 million	0.06 million
# sources	1984	481	413
# outliers $> 5\sigma$	106	13	7
% outliers	5.0 %	2.6 %	1.7 %
$\alpha$ wRMS	536 $\mu$ as	439 $\mu$ as	434 $\mu$ as
$\delta$ wRMS	544 $\mu$ as	455 $\mu$ as	423 $\mu$ as
$R_x$	32 +- 13	100 +- 24	56 +- 24
$R_y$	5 +- 11	-7 +- 21	32 +- 21
$R_z$	28 +-13	0 +- 23	15 +- 24
$\Delta\alpha$ vs. $\delta$ tilt ( $\mu$ as/deg)	0.28+- 0.25	1.70 +- 0.55	-2.82 +- 0.58

Credit: Jacobs et al, IAU 330, 2017

Hints that results improve by going to higher radio frequency  
However, the above results do not use exact same objects





# Gaia Optical vs. X/Ka frame tie

- Gaia Data Release #1 2016 September:  
median sigmas  $\sim 500 \mu\text{as}$  per component  
Gaia Data release #2 2018 April
- VLBI XKa radio sigmas  $\sim 100 \mu\text{as}$  per component and improving
- 3-D rotational sigmas  $\sim 20 \mu\text{as}$
- Potential for rotation sigmas  $\sim 5 \mu\text{as}$  per frame tie component  
after which the limitation is the number of XKa sources.
- Expect that accuracy will be limited by systematic errors—  
In particular zonal errors vs. Dec in the VLBI frames



# Conclusions

## I. Concepts and Background:

- A. Desire nonrotating, non-accelerating frame. Use a quasi-inertial with some accelerations
- B. Networks: The instruments used to build the frame  
ad hoc, VLBA, EVN, Global, NASA-ESA DSN, ESA, LBA, AuScope, etc.
- C. Brief history of Astrometry: The 'fixed' stars aren't so fixed.
  - 1. Precession, proper motion, nutation, parallax
  - 2. Invention of radio astronomy. VLBI's pursuit of sub-milli-arcsecond accuracy.

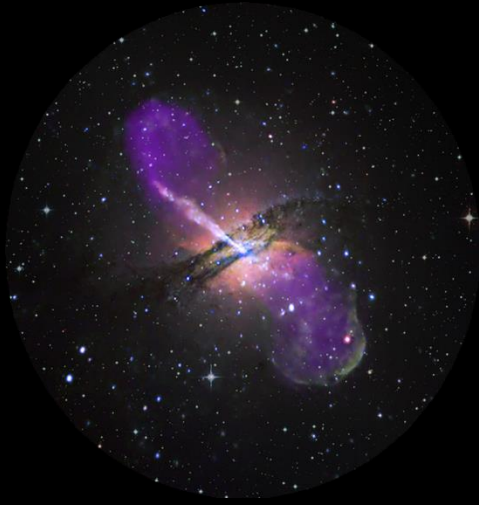
## II. Celestial Frames built using VLBI

- A. Surveys: Single dish,  
connected arrays: Jodrell-VLA (JVAS, north), ATCA 20 GHz (AT20G, south),  
VLBI ~mas: VLBA Cal Survey (north), LBA Cal Survey (south)
- B. ICRF-1 (1998): The IAU moves to from optical (stars) to 212 Defining quasars.  
ICRF-2 (2009) : 295 defining sources, 3414 total, 40  $\mu$ as systematic floor
- C. Higher frequency radio frames: K & Q (24 & 43GHz), X/Ka (32 GHz)  
100 to 200  $\mu$ as agreement with SX

## III. The Path to the Future:

- A. Error Budgets: a tool for allocating resources for improvement
- B. Case study: Improved X/Ka Frame: SNR, Instrumentation, Troposphere, **Geometry**
- C. ICRF-3 goals: 2018, improve south, improve VCS, improve K & X/Ka
- D. Gaia: 2024 the return of optical, 500,000 quasars, ~billion total sources

# Thank You for your Attention



*Estrellas, que rodean, señas,  
Ojos, mis ojos captan la luz,  
suave palpar de mi corazón,  
llevado en alto por la brisa  
vuelo de mi alma,  
libre, nacida de nuevo  
bajo un cielo maravilloso.*

*-C.S. Jacobs : ©2013*

*(inspirado en un verso de Abraham Kron)*



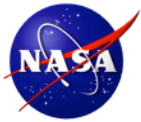
Photo: ©1986 C.S. Jacobs, All rights reserved



*Y yo, minimo ser,  
ebrio del gran vacío constelado,  
a semejanza, a imagen del misterio,  
me sentí parte pura del abismo,  
rodé con las estrellas,  
mi corazón se desató en el viento.*

*- Pablo Neruda*

*And I, infinitesimal being,  
inebriated on the great starry void,  
likeness, image of mystery,  
I felt myself a pure part of the abyss,  
I rode with the stars,  
my heart broke free onto the open sky.*



# Overview

## I. Concepts and Background:

- A. What is a Reference frame? Concepts, uses, desired properties
- B. Networks: The instruments used to build the frame  
ad hoc, VLBA, EVN, Global, NASA-ESA DSN, LBA, AuScope, etc.
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## II. Celestial Frames built using VLBI

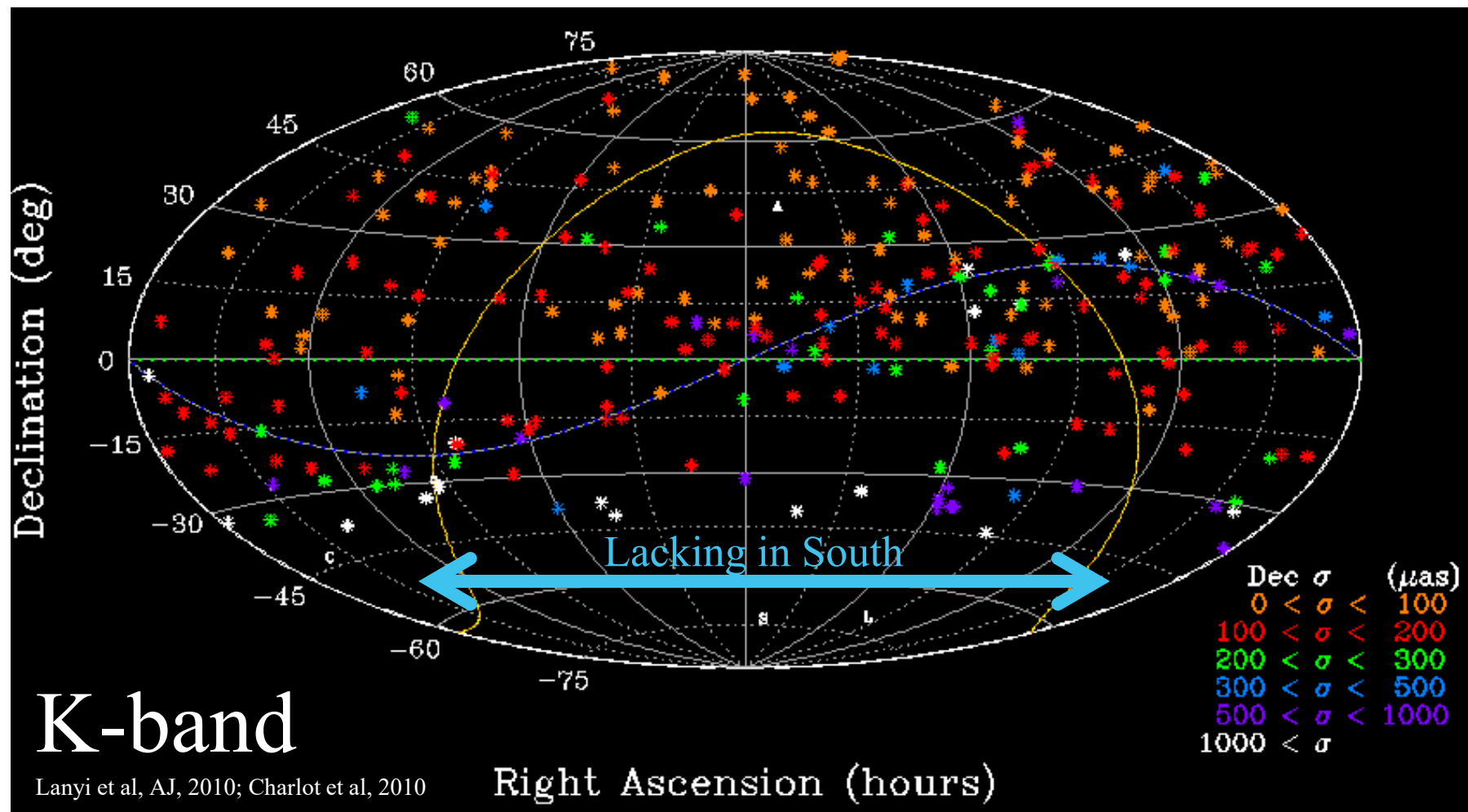
- A. Surveys: Single dish, connected array: JVAS, AT20G, and VLBI: VCS, LCS
- B. ICRF-1, ICRF-2: The IAU moves to from optical (stars) to radio (quasars)
- C. Higher frequency radio frames: K&Q (24 & 43GHz), X/Ka (32 GHz)

## III. The Path to the Future:

- A. Error Budgets: a tool for allocating resources for improvement**
- B. Case study: Path to Improved X/Ka (8.4/32 GHz) Frame**
- C. ICRF-3: the next standard radio frame**
- D. Gaia: an optical frame with high accuracy**



# III.C. ICRF-3 Needs



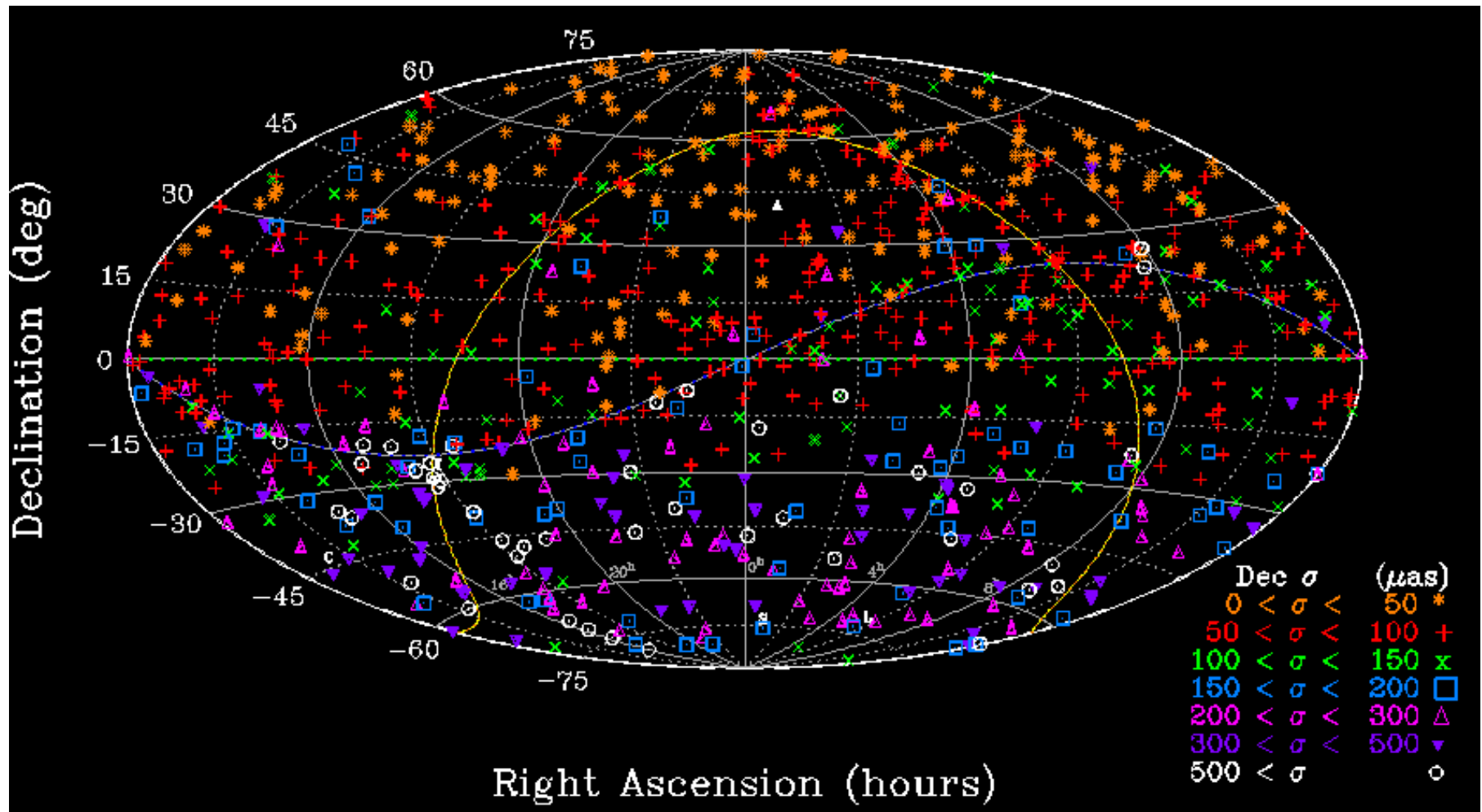
K-band frame (24 GHz) lacking in the south for Dec  $< -30$  deg (limit of VLBA work)

K-band: HartRAO to Hobart, Tasmania

New K-band CRF collaboration: cf. Bertarini et al & de Witt et al, Journees 2013

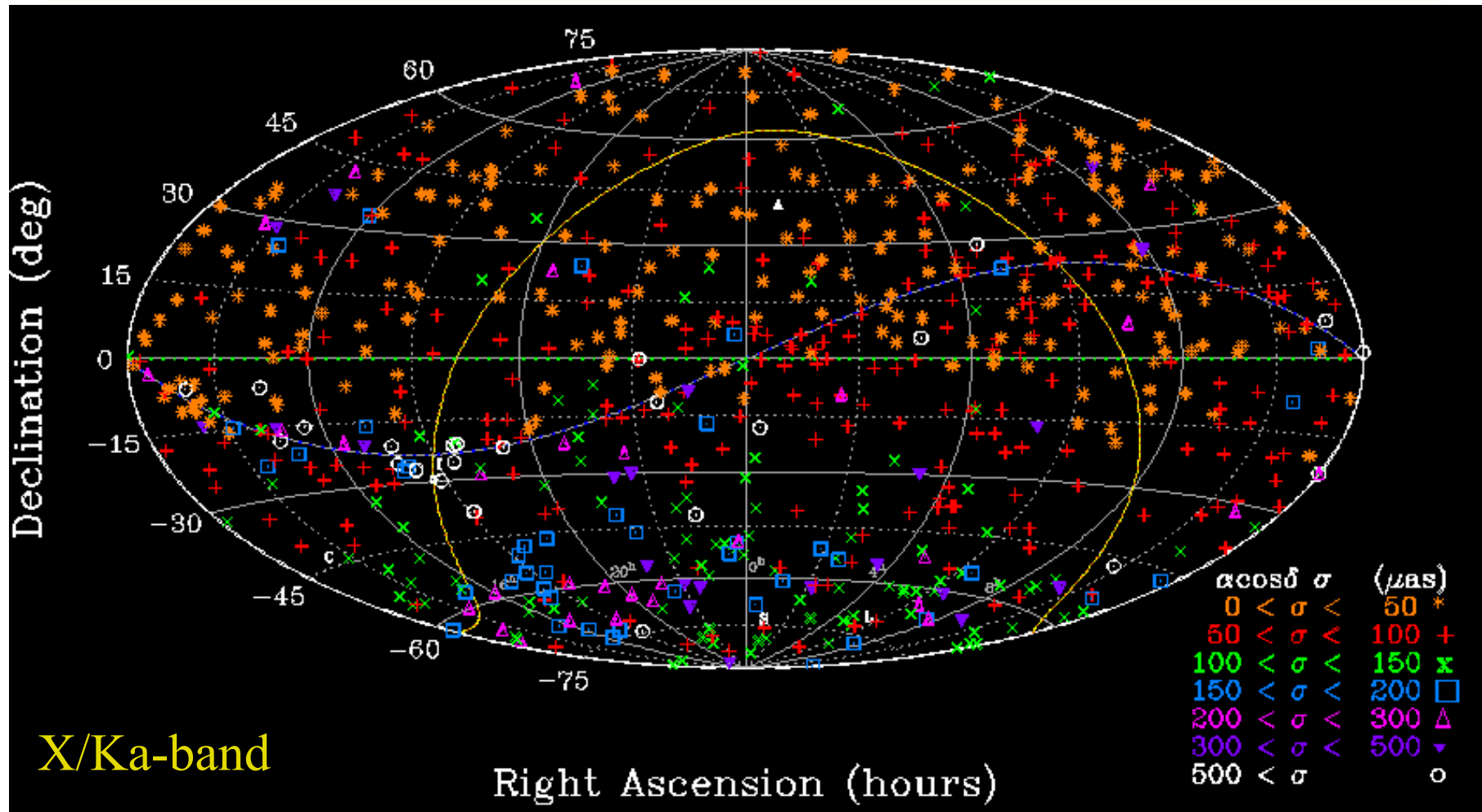


# K-band (24 GHz) CRF: 826 sources

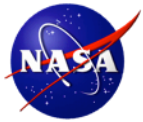


VLBA 35 sessions @2Gbps to densify the north (*de Witt et al, EVGA, 2017*)

Hart-Hobart (Tianma): 15 sessions. Archive (*Lanyi et al, 2010, Petrov et al, 2006*).



- **Deficiency: Weaker in the south.** S. cap 134 sources (dec < -45); 27 ICRF2 Defining
- Full sky coverage (681 sources): NASA baselines CA to Madrid & Australia + recently added ESA Malargüe, Argentina to Tidbinbilla, Australia, PI: Jacobs



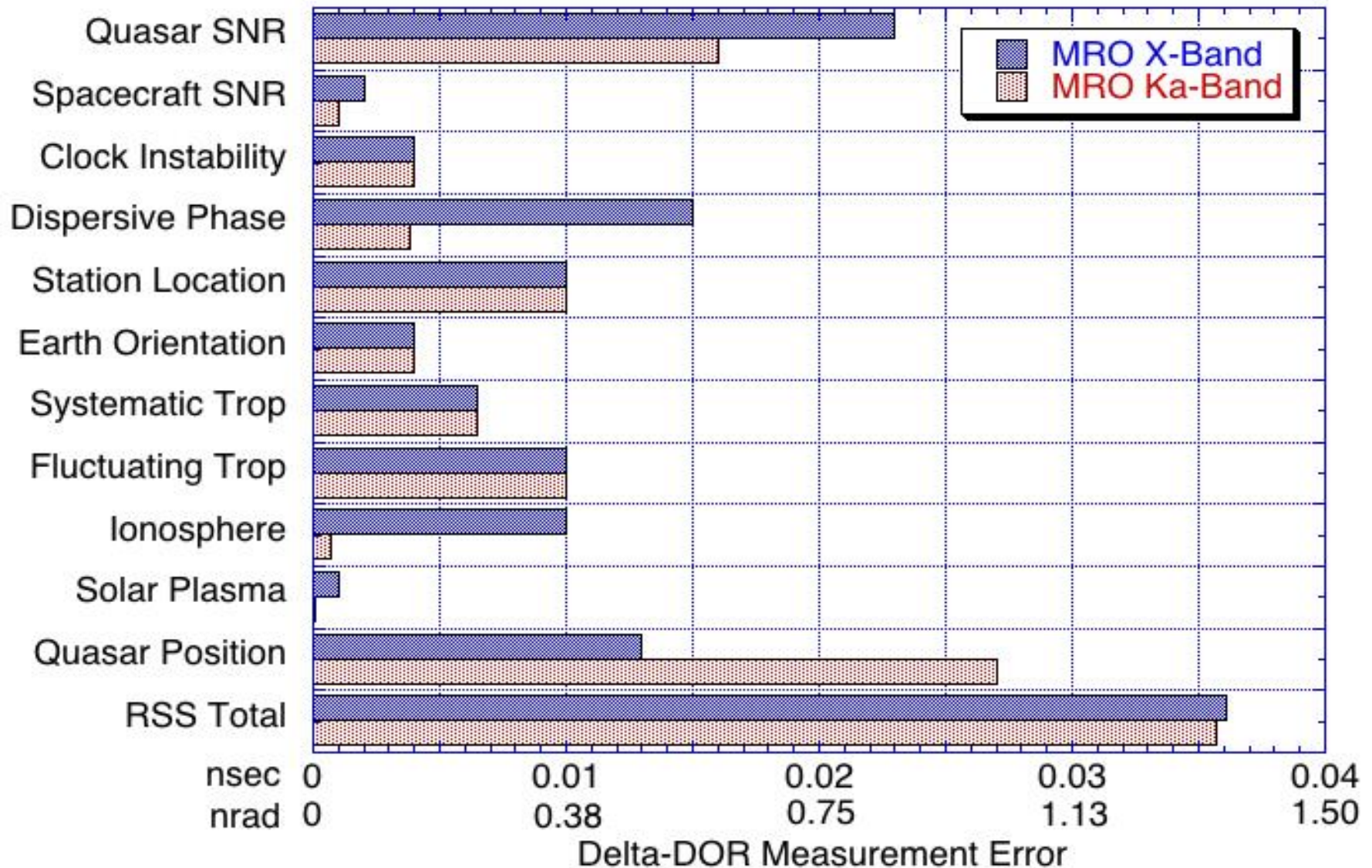
# Error Budget for Reference Frame VLBI

*The Tall Tent Poles*





# $\Delta$ VLBI Error Budget







# Overview

## I. Concepts and Background:

- A. What is a Reference frame? Concepts, uses, desired properties
- B. Networks: The instruments used to build the frame  
ad hoc, VLBA, EVN, Global, NASA-ESA DSN, LBA, AuScope, etc.
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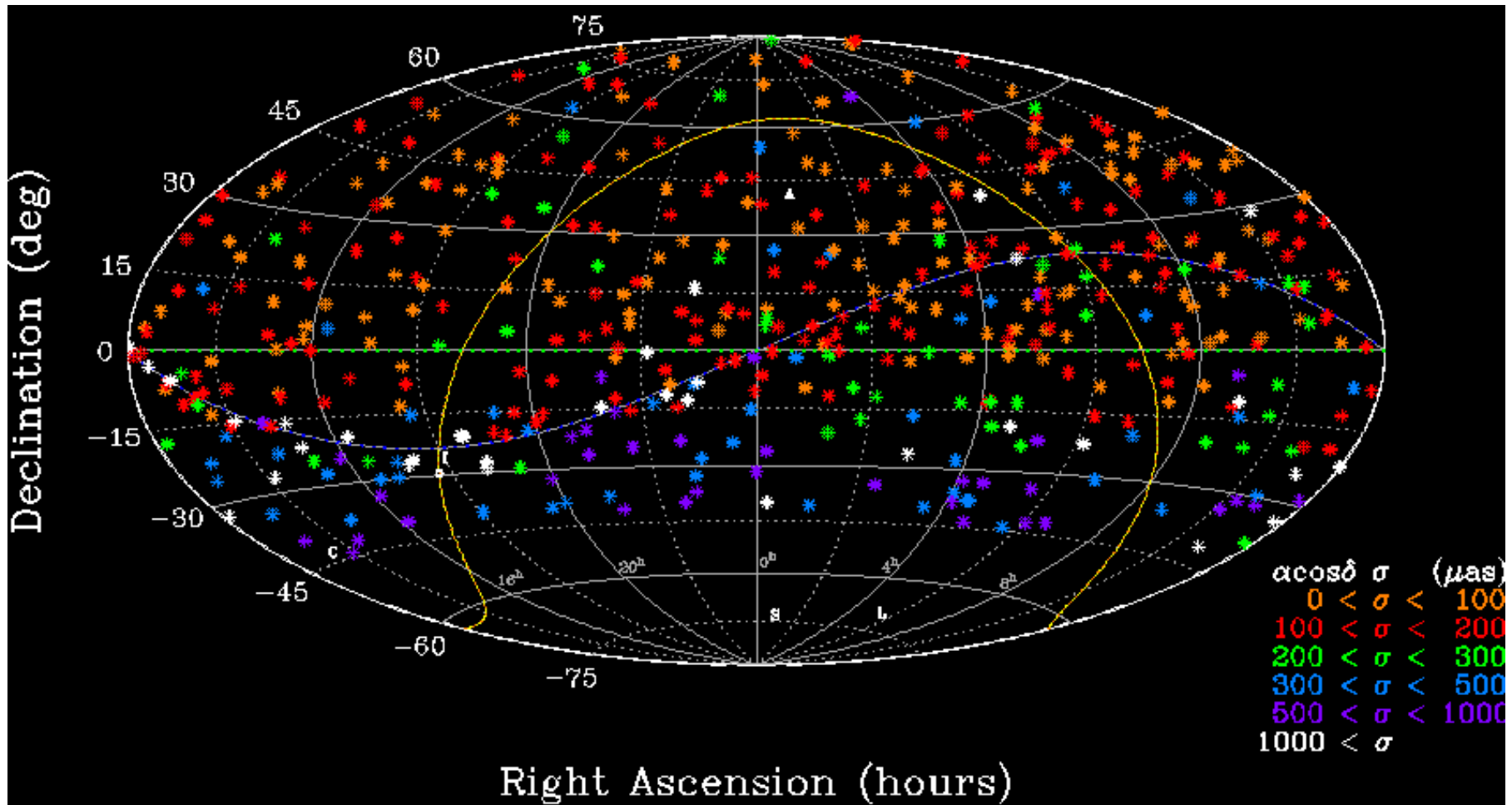
- A. Surveys: Single dish, connected array: JVAS, AT20G, and VLBI: VCS, LCS
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- C. **ICRF-3: the next standard radio frame**
- D. **Gaia: an optical frame with high accuracy**



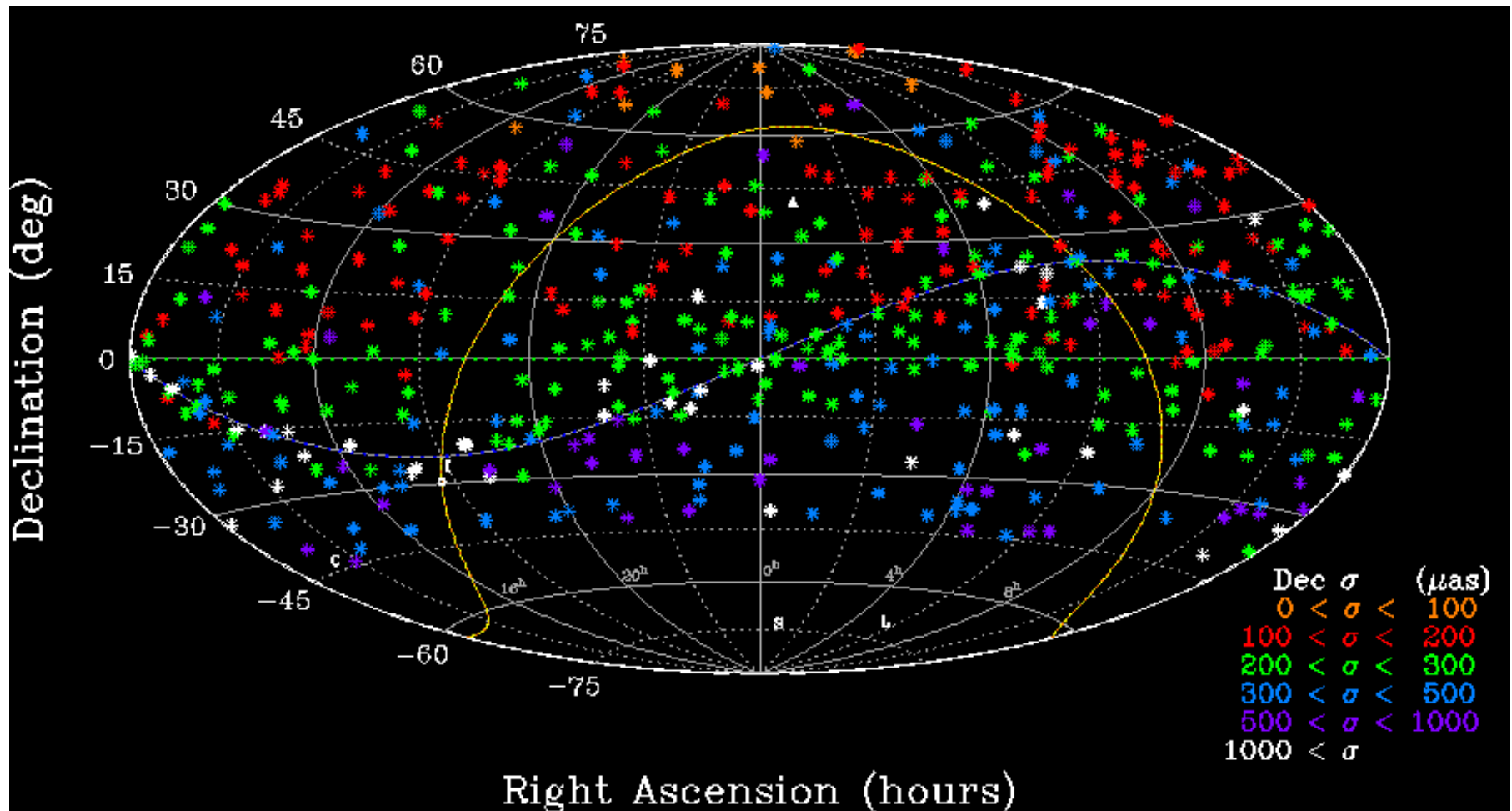
# Status 2012: X/Ka RA results 482 Sources



Cal. to Madrid, Cal. to Australia. **Weakens south of Dec = -15deg**



# Status 2012: X/Ka Dec results 482 Sources



Cal. to Madrid, Cal. to Australia. **Weakens southward.** **No  $\Delta$ Dec tilt**



# Focus Work on the Tall Tent Poles

Systems Analysis shows dominant Errors are

- **Limited SNR/sensitivity**
  - already increased bit rates in 2009: 112 to 448 Mbps.
  - 2048 Mbps fringes May 2013. 1-2 Gbps operational in 2014
- **Instrumentation:** already building better hardware
  - BWG phase calibrators, Digital baseband conversion & filters
- **Troposphere:** better calibrations being explored
- **Weak geometry in Southern hemisphere**
  - Limits accuracy to about 1 nrad (200  $\mu$ as) level
  - Need observations below Declination of -45 Deg!
  - DSN at X/Ka had only Canberra, Australia (DSS 34)
  - Needed 2nd site in the Southern hemisphere especially for upcoming southern ecliptic missions: Maven (2014), Exo-Mars (2016), InSight (2018).



# Attacking the Error budget

- **SNR can be improved +6 to 9 dB!**
- Instrumentation:
  - Phase calibration with test signals
  - Digital Baseband Conversion & Filtering
- Troposphere cals: WVR
- Southern Geometry





# Results have been limited by SNR

## Solution:

### 1) More bits:

112 Mbps 2005

448 Mbps 2010

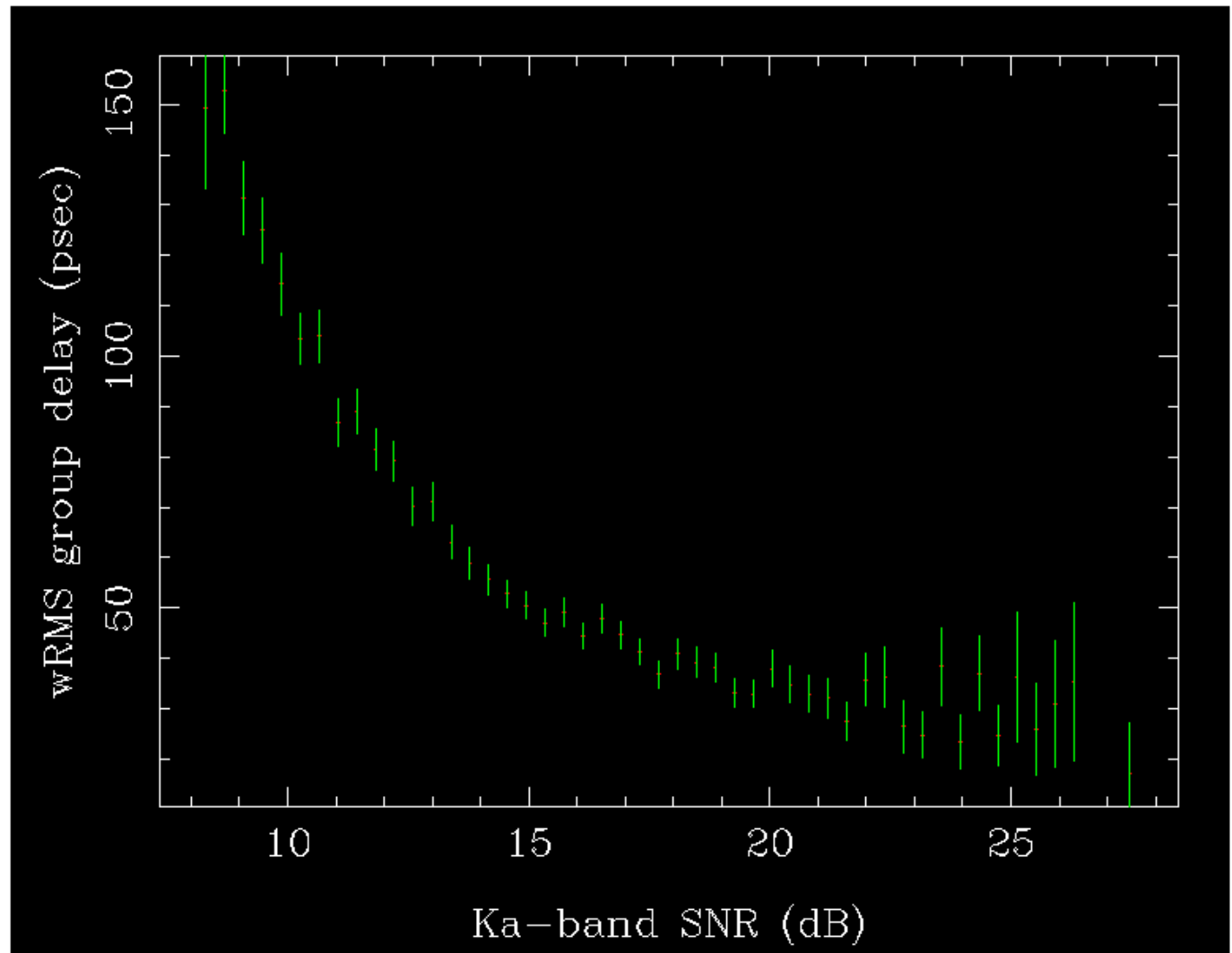
2014 Mbps 2013

4.3 increase sensitivity  
+6.3 dB SNR

### 2) Ka pointing

Now with improved  
Pointing calibrations  
~3 dB more SNR

Total vs. early passes  
+9 dB SNR increase!



Results have been SNR limited for SNR < 30 (15 dB)



# Phased implementation, testing

- Data rate: 43 passes @ 112 Mbps (X/Ka 56/ 56 Mbps)

3 passes @ 224 Mbps (X/Ka 80/144 ) ~ 3X

30 passes @ 448 Mbps (X/Ka 160/288 ) ~ 5X

current @ 2048 Mbps (X/Ka 640/1408 ) ~25X

Total Ka improvement 56 to 1408 Mbps => 5-10 psec del. precision

**Reduces SNR below troposphere with increased Ka sensitivity!**  
**Thus SNR will longer be the tallest tent pole.**

Credit: NASA: C. Jacobs, D. Bagri, E. Clark, C. Garcia-Miro, C. Goodhart, S. Horiuchi, S. Lowe, E. Moll, L. Skjerve, L White

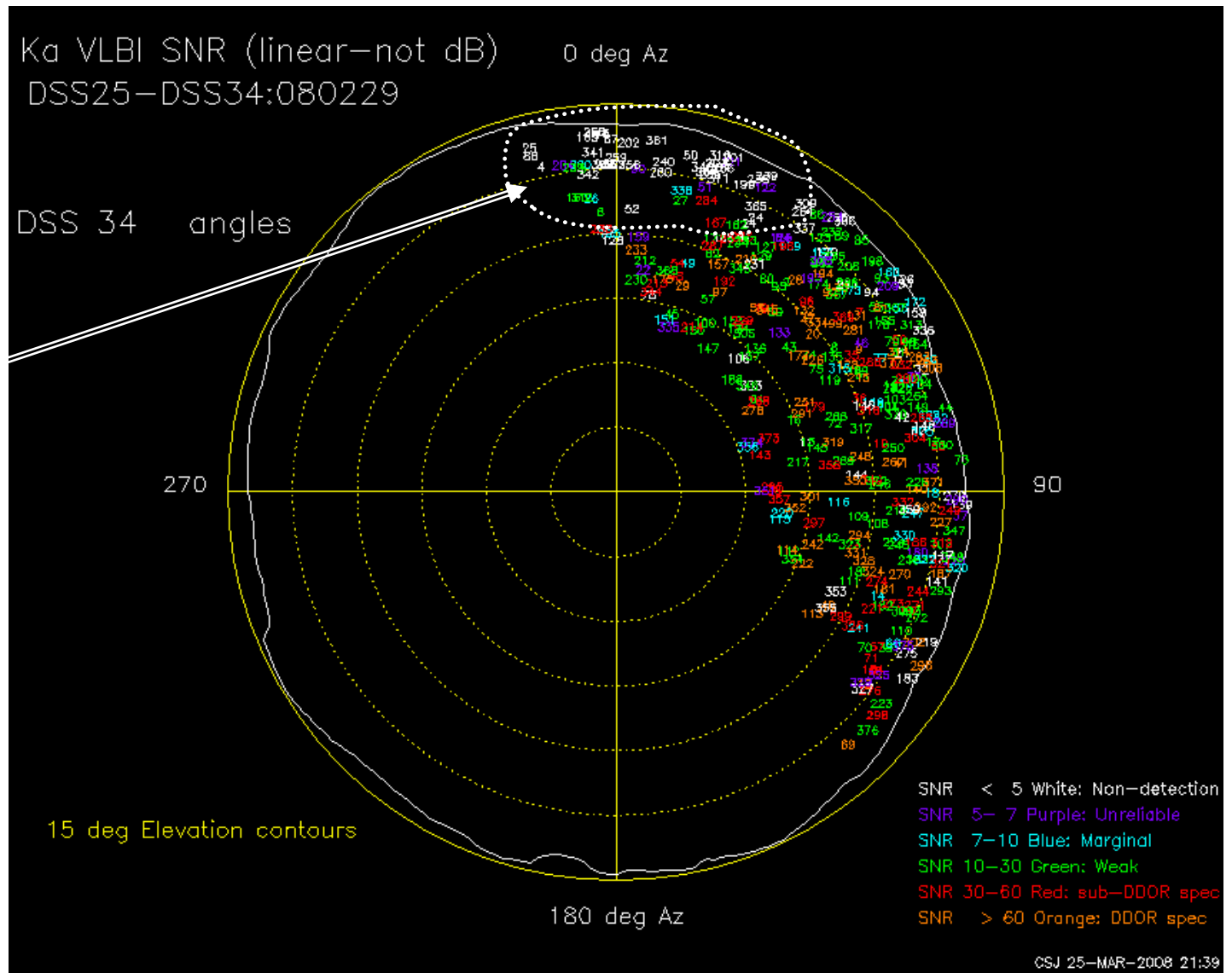


# Example: Ka-band Antenna Pointing

White pts.  
Represent  
Non-detection

Note Northern  
concentration  
of non-detects

Later, we got  
independent  
confirmation  
from ACME  
automated  
bore sight  
system of  
18 mdeg  
errors



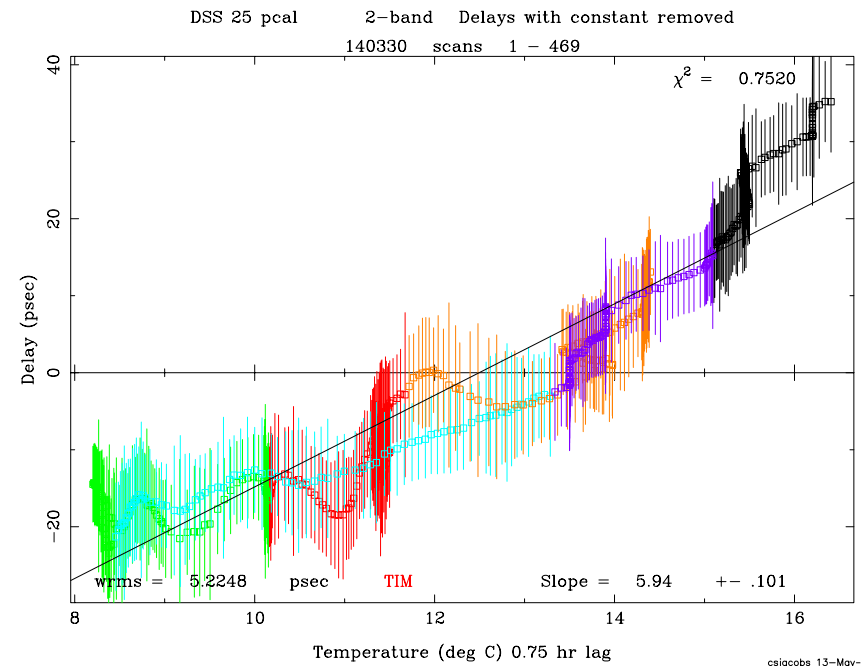
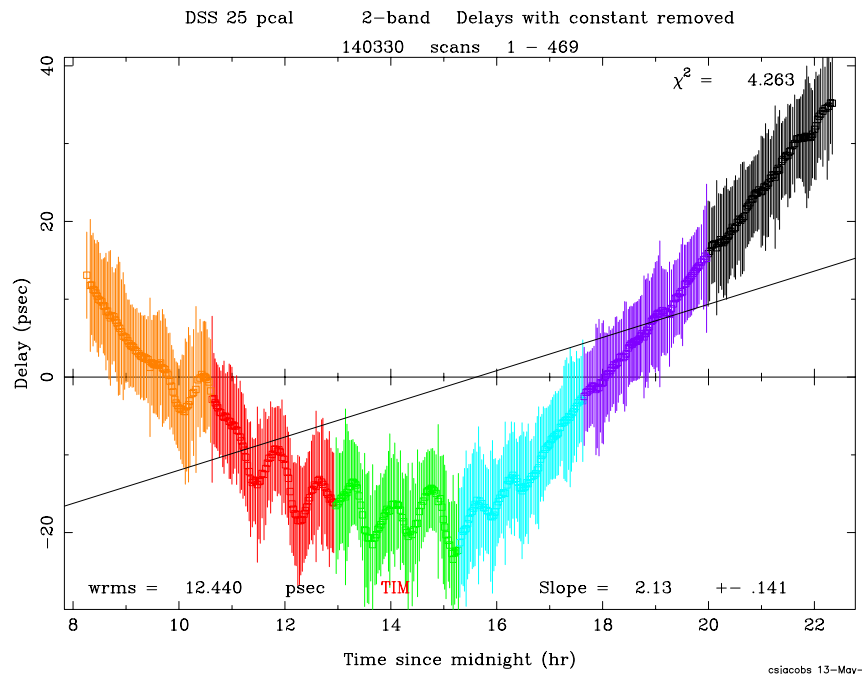


# Attacking the Error budget

- SNR can be improved +8 dB!
- **Instrumentation:**
  - Phase calibration with test signals
  - Digital Baseband Conversion & Filtering
- Troposphere cals: WVR
- Southern Geometry



# Results limited by instrumental delays



- **Problem:** diurnal thermal effect on cables, time lag  $\frac{3}{4}$  hour
- **Solution:** Ka-band Phase calibrator, uses test tones to measure delay
- **Unit is now operational in California**  
Spain and Australia expected to have units in 1-2 years



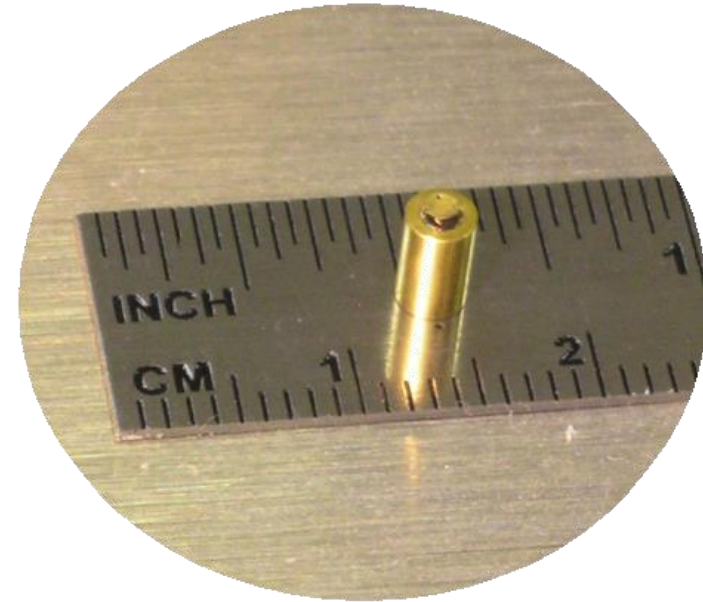


## BWG Phase Calibrator

- Concept: Tunnel diode  
Alan Rogers et al (Haystack)
- JPL prototype BWG phase cal:  
Hammel, Tucker, & Calhoun,  
JPL Progress Report, 2003
- Production units: Blake Tucker

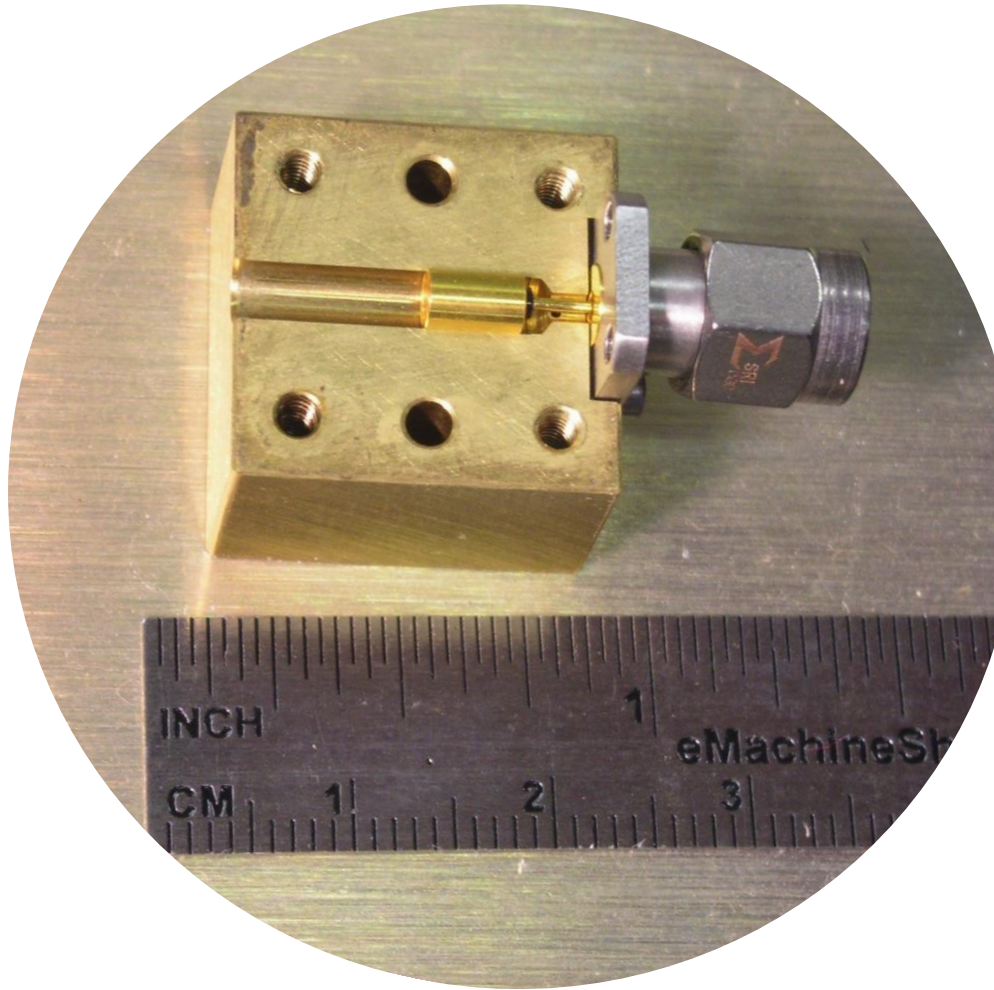
[http://tmo.jpl.nasa.gov/progress\\_report/42-154/154H.pdf](http://tmo.jpl.nasa.gov/progress_report/42-154/154H.pdf)

<http://adsabs.harvard.edu/abs/2003IPNPR.154....1H>

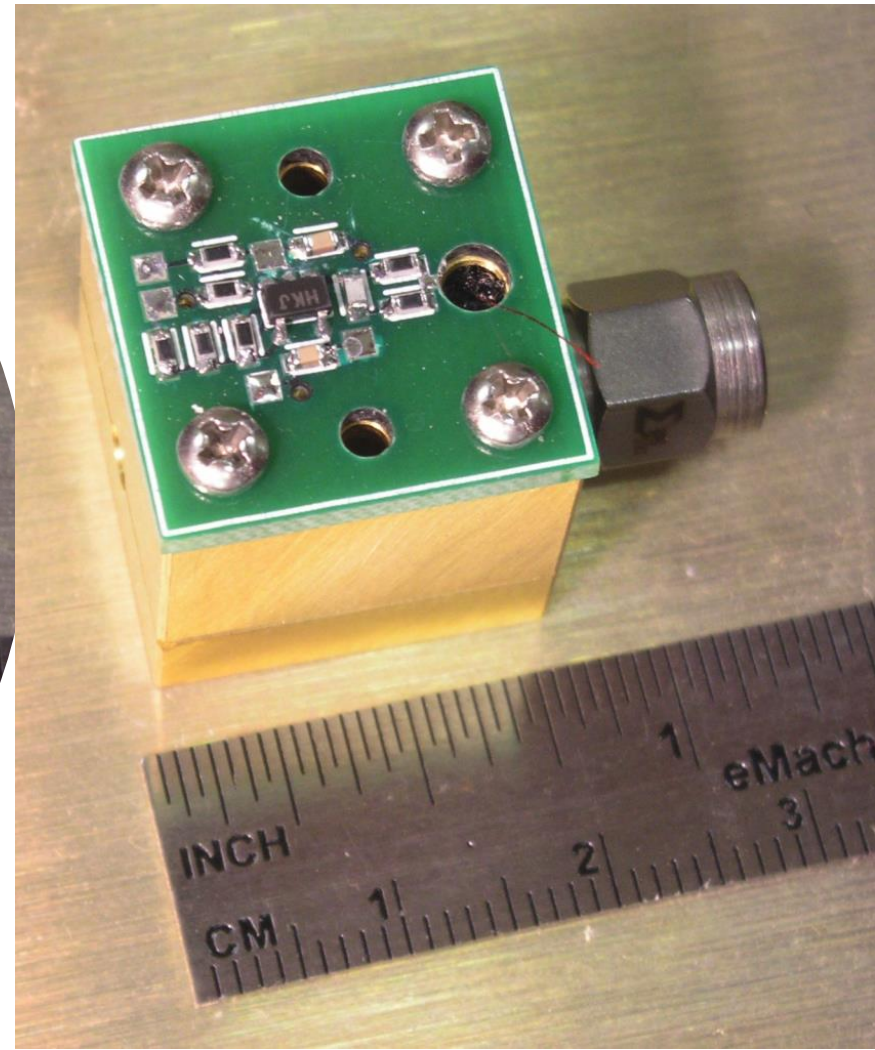


Tunnel Diode Chip  
0.055" diameter by  
0.020" thick  
Mounted on  
0.119" diameter carrier  
for solid grounding

# Beam Wave Guide phase calibrator



Direct interface to K connector  
inside coaxial structure.



Pulse driver mounted as close as possible  
and fed through coaxial structure  
to minimize rise time and ringing





# *Sample, Baseband convert, Filter, Record*



IF select switch:  
12 inputs allows  
multiple bands,  
multiple antennas



Command & Control

Mark-5C recorder



Sampler: 1280 MHz, 8-bit/sample



Copper to fiber, **Digital filter**, Format



# Summary of Instrumental Improvements

<u>Instrument</u>	<u>MkIV</u>	<u>DBE/Mk5-C</u>	<u>Comment</u>
<b>Filters</b>	<b>Analog 7-pole Butterworth</b>	<b>Digital FIR phase linear</b>	<b>removes phase ripple in channel</b>
<b>Spanned bandwidth</b>	<b>360 MHz</b>	<b>500 MHz</b>	<b>Mk4 limit 1.4X improvement</b>
<b>Data rate @ start</b>	<b>112 Mbps</b>		<b>DSN SNR limited</b>
<b>@ max.</b>	<b>896 Mbps</b>		<b>trop/inst. limited</b>
<b>@ start</b>		<b>2048 Mbps</b>	<b>trop/inst. limited</b>
<b>@ max.</b>		<b>4096 Mbps</b>	<b>6X sensitivity</b>
<b>Phase Cal: HEF/70m</b>	<b>Yes</b>	<b>Yes</b>	
<b>BWG</b>	<b>No</b>	<b>Yes</b>	<b>removes 100s of psec</b>



# Attacking the Error budget

- SNR can be improved +8 dB!
- Instrumentation:
  - Phase calibration with test signals
  - Digital Baseband Conversion & Filtering
- **Troposphere cals: WVR**
- Southern Geometry



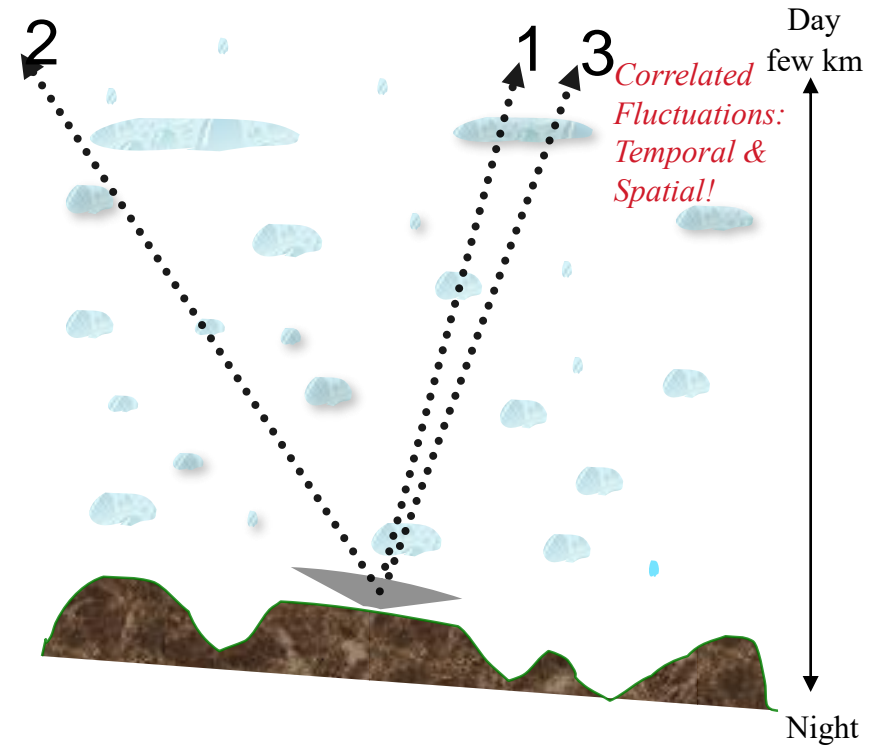


# Troposphere Solution 1: Better Estimation

- Modified Least Squares to account for observation correlations -- both temporal and *spatial*
- Use Kolmogorov frozen flow model of Treuhaft & Lanyi (Radio Sci. 1987)  
<http://adsabs.harvard.edu/abs/1941DoSSR..32...16K>  
<http://adsabs.harvard.edu/abs/1987RaSc...22..251T>
- Model increases information available to the estimation process
  - 1) Reduces parameter biases
  - 2) Reduces parameter sigmas
- Validation: Currently improves agreement X/Ka vs. S/X catalogs by about 10% in Declinations.

Expect ~30% after SNR & phase cal errors peeled away to reveal troposphere errors.

Romero-Wolf & Jacobs, IVS, 2012 [http://www.oan.es/gm2012/pdf/oral\\_id\\_119.pdf](http://www.oan.es/gm2012/pdf/oral_id_119.pdf)





# Calibrating Troposphere Turbulence

- JPL Advanced Water Vapor Radiometer

- ~ 1 deg beam better matches VLBI
  - improved gain stability
  - improved conversion of brightness temperature to path delay

Tanner & Riley, Radio Sci., 38, 2003

<http://adsabs.harvard.edu/abs/2003RaSc...38.8050T>



- Initial demos show 1mm accuracy  
Goldstone-Madrid 8000 km baseline  
using X/Ka phase delays

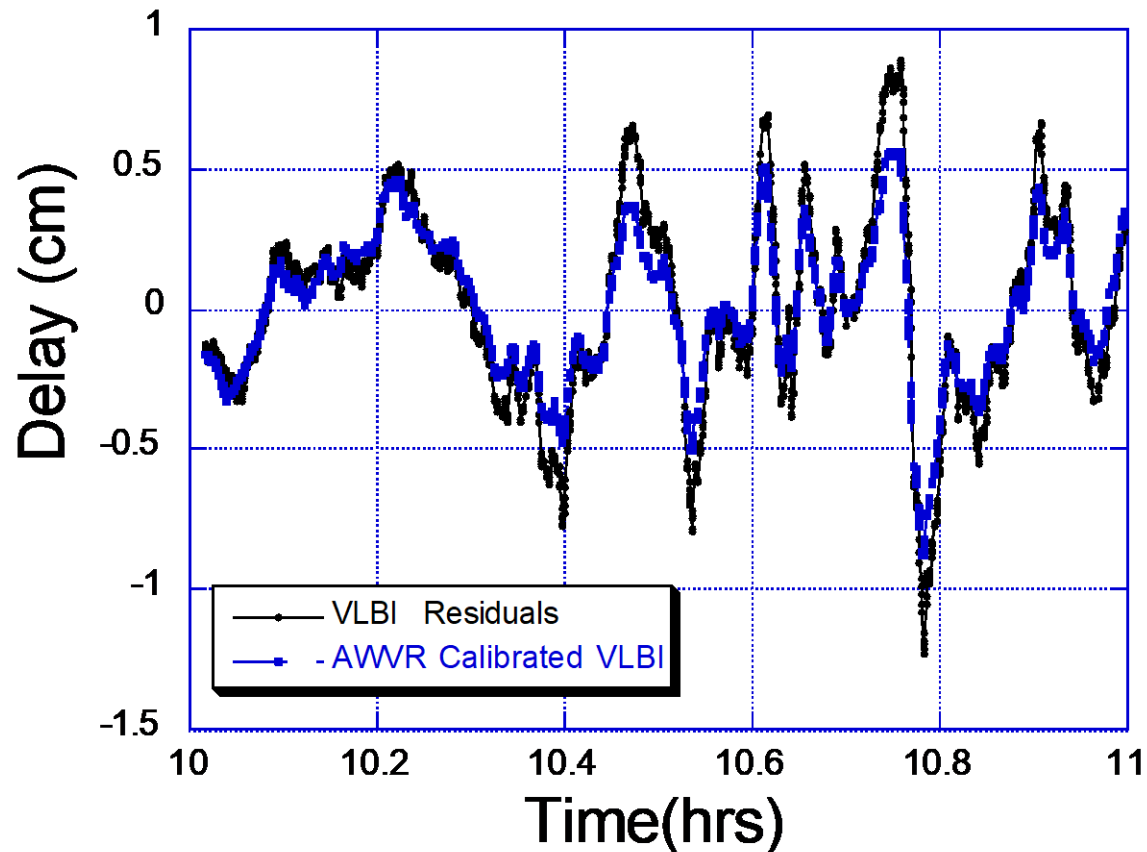
*Jacobs et al, AAS Winter 2005.*

*Bar Sever et al, IEEE, 2007.*

<http://adsabs.harvard.edu/abs/2007IEEEP..95.2180B>

- A-WVRs deployed at Goldstone/Madrid  
Seeking funding for Tidbinbilla, Aus
- **A-WVR not used yet for Operations**

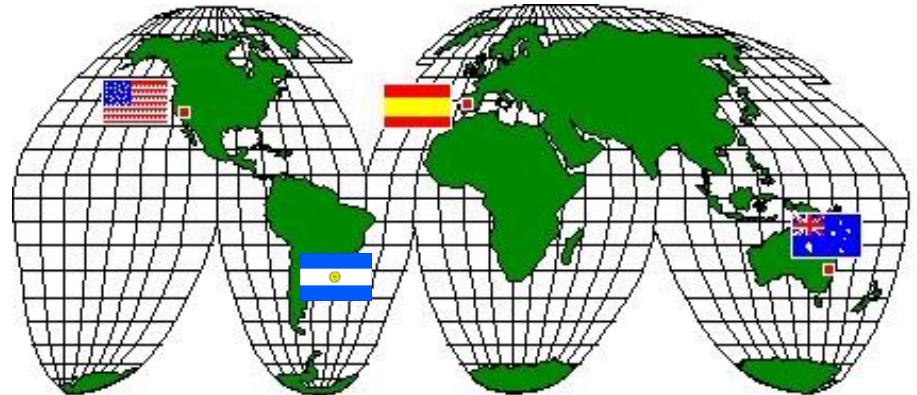
## VLBI Delay Residuals DOY 200 Ka-Band DSS26-DSS55





# Attacking the Error budget

- SNR can be improved +8 dB!
- Instrumentation:
  - Phase calibration with test signals
  - Digital Baseband Conversion & Filtering
- Troposphere calcs: WVR
- **Southern Geometry**

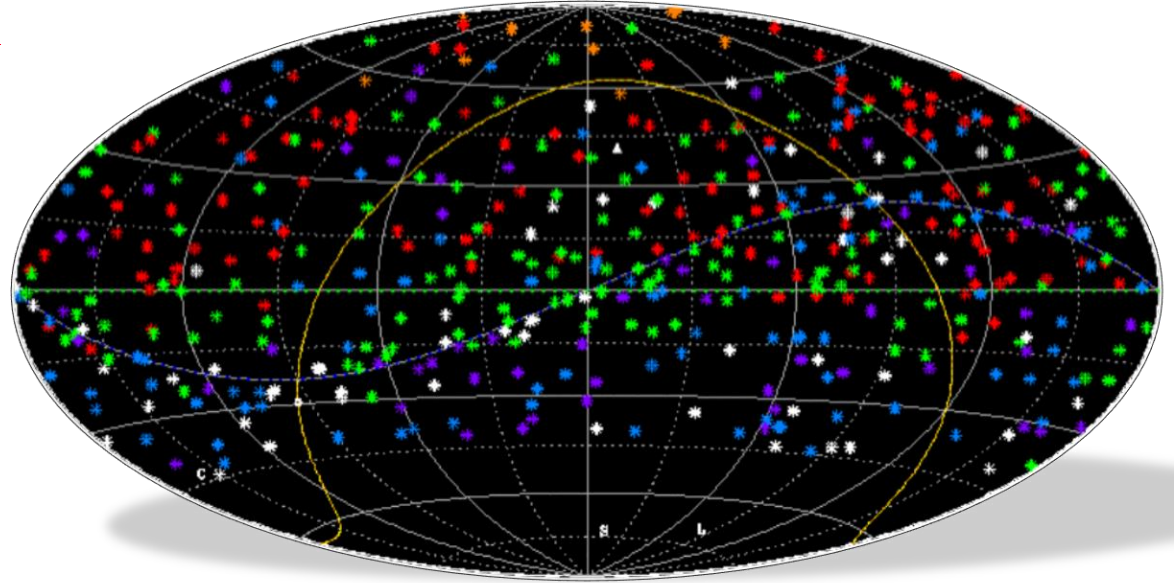




# Need 2nd Station in South

- Almost no Ka sources meet the accuracy goal south of equator!
- No coverage of South polar cap (-45 to -90 Dec)
- DSN weakly covers southern Ecliptic: only one strong baseline as California-Spain is weak in south

DSN X/Ka Frame after 50 sessions



## Declination 1-sigma

Orange	0-0.5 nrad meets future $\Delta$ DOR spec
Red	0.5-1.0 current $\Delta$ DOR spec
Green	1.0-1.5
Blue	1.5-2.5
Purple	2.5-5.0
White	5.0



# Southern VLBI Stations?

- ESA Deep Space Antennas (DSA-1, 2, 3)
  - New Norcia, Australia S/X (DSN Canberra, 3000km)
  - **Malargue, Argentina: Ideal,**



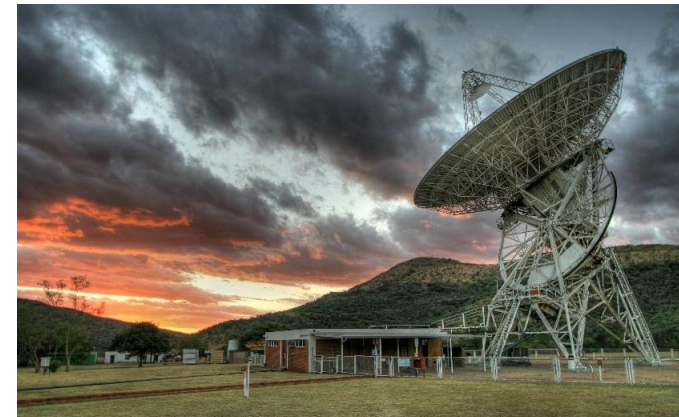
Operational Jan 2013, NASA-ESA collaboration

- 35m, X/Ka-band, 9,500 km baseline
- Dry desert site is good for Ka-band
- HA-Dec coverage: Tidbinbilla to Malargue:



Malargue 35-m X/Ka, photo credit: L.A. White, Dec. 2012

- HartRAO, South Africa  
26-meter Resurfaced in 2005 (0.5mm RMS) efficient to 22 GHz  
K-band CRF: *DeWitt et al, and Bertarini et al, Journees 2013.*
- Hobart, Tasmania, 12-m (S/X) and 26-m S/X, K-band
- Warkworth, New Zealand, 12-m S/X
- Tidbinbilla, Australia: S/X (34m), X/Ka (34m), K (70m)

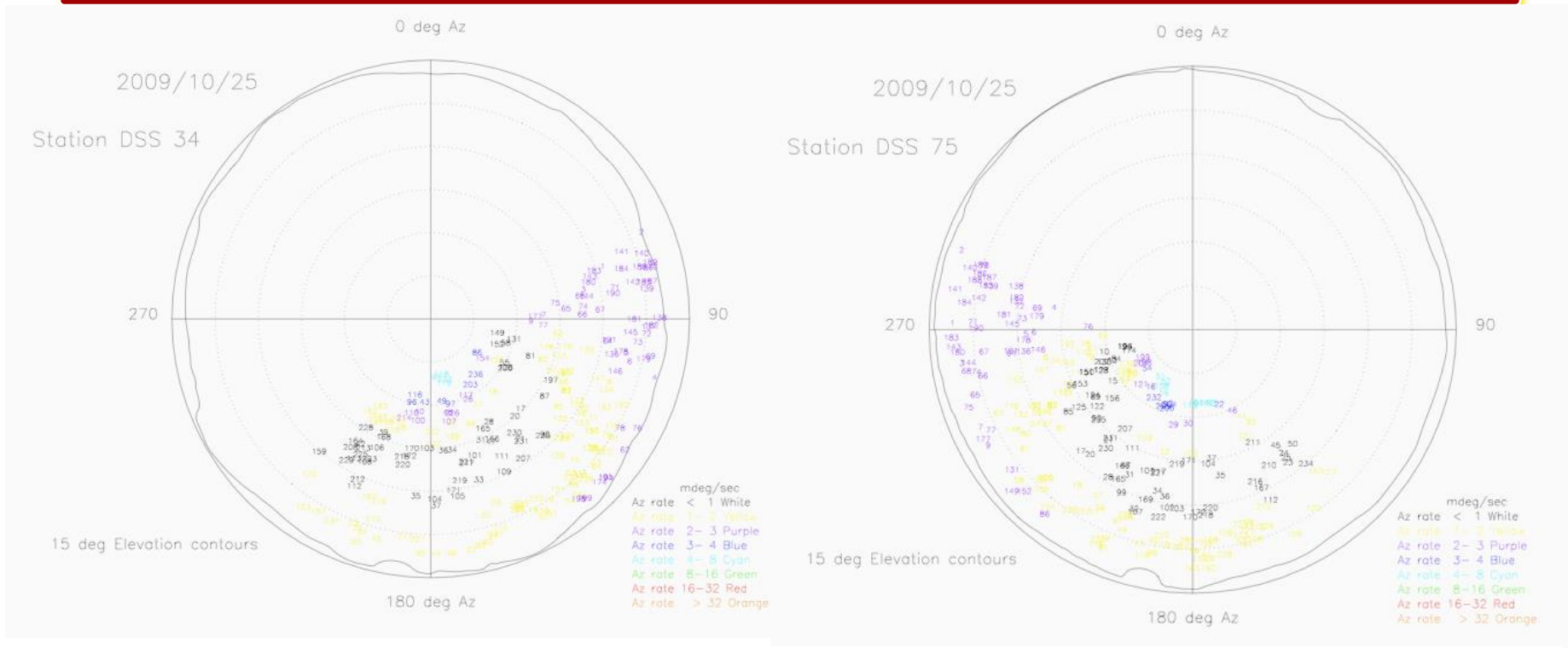


HartRAO 26-meter Photo credit: Thomas Abbott

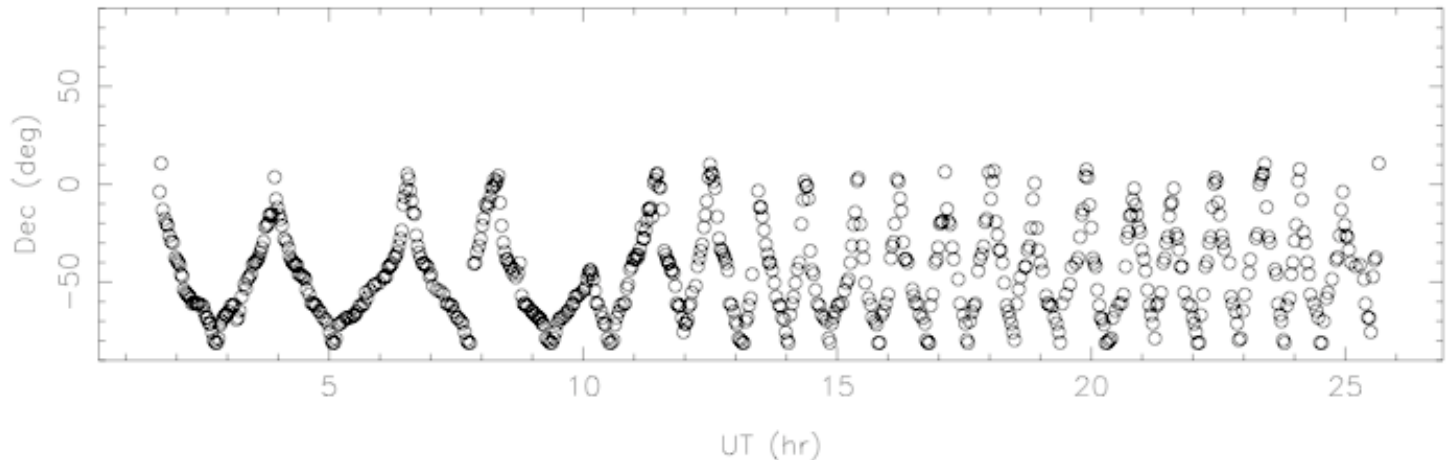


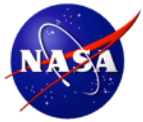


# DSS 34 to Malargue, Argentina (DSA-3)

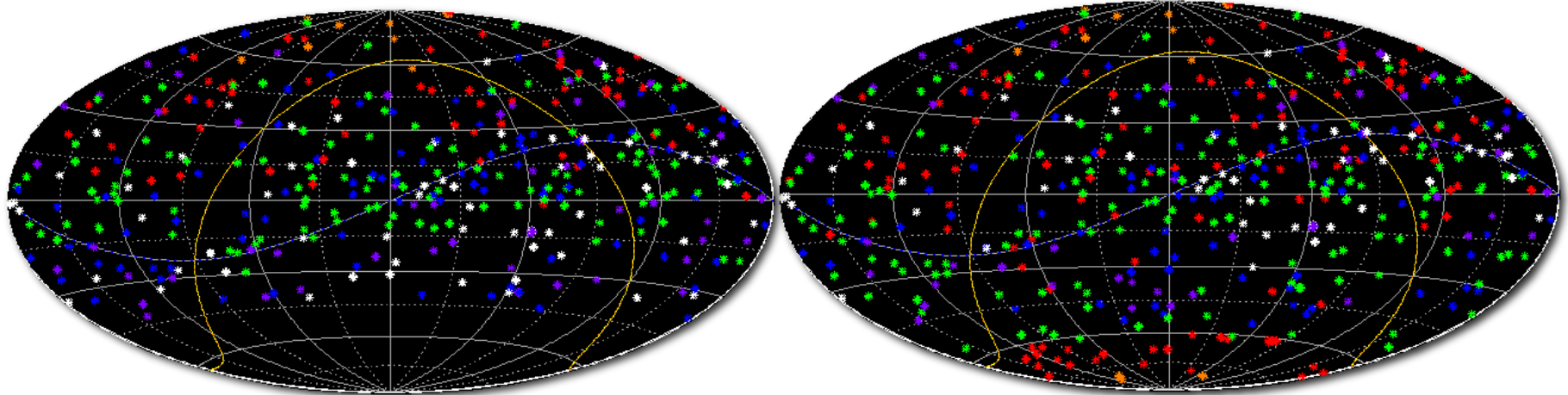


Simulated  
Coverage:  
**Dec +10 deg  
to -90 deg**





# Simulation of Added Southern Station



*Before Southern Data*

- 50 real X/Ka sessions augmented by simulated data  
simulate 1000 group delays, SNR = 50  
~9000 km baseline: Australia to S. America or S. Africa
- Completes Declination coverage: cap region -45 to -90 deg  
200  $\mu$ as (1 nrad) precision in south polar cap,  
mid south 200-1000  $\mu$ as, all with just a few days observing.

*After*

Declination Sigma

Orange: < 100  $\mu$ as

Red: < 200

Green: < 300

Blue: < 500

Purple: < 1000

White: > 1000

Bourda, Charlot, Jacobs, 2011 <http://adsabs.harvard.edu/abs/2011EAS....45..377B>

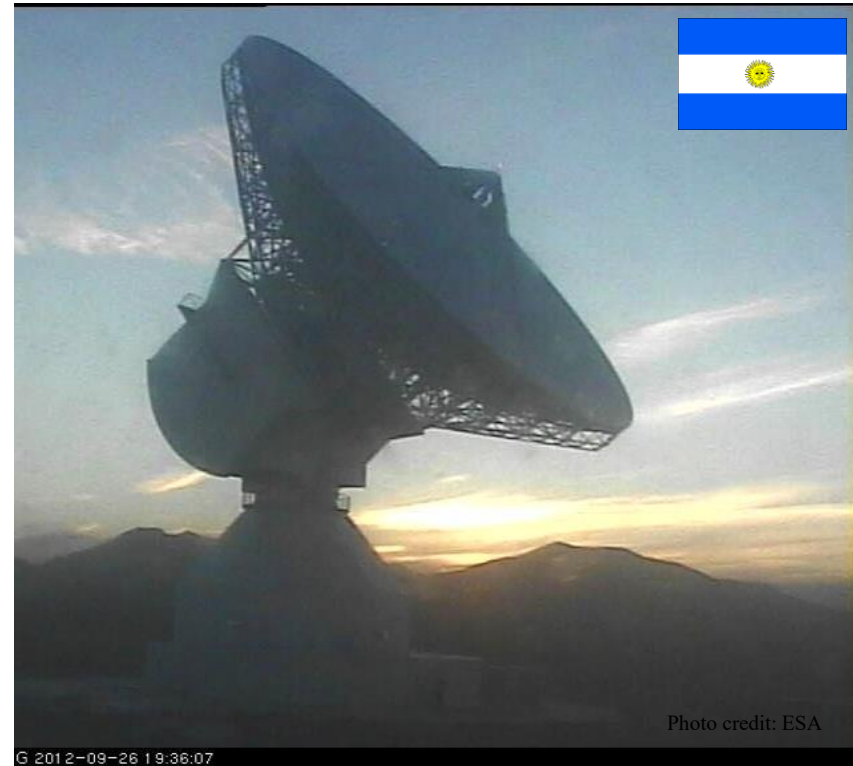


# Malargüe: The Next X/Ka VLBI Station



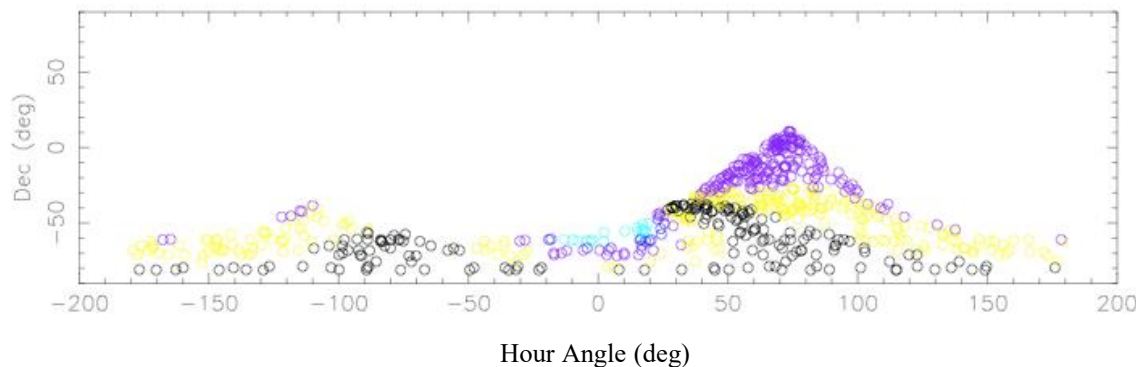
X/Ka: ESA Deep Space Antenna DSA 03

- **Malargüe, Argentina**
- Fall-2012 NASA/ESA collaboration
- 35-m, X/Ka-band, 9,500 km baseline  
Argentina-Australia covers south polar cap  
Full sky coverage for X/Ka!!
- Argentina-California & Australia-California  
orthogonal baselines for mid-latitudes
- High (1.5km), dry desert site: good for Ka-band
- HA-Dec coverage: Tidbinbilla to Malargüe:



Malargüe, Argentina 35-meter as of 26 Sept .2012

ESA Deep Space Antenna  
*X/Ka-band capable*







# X/Ka stations for Celestial Frame



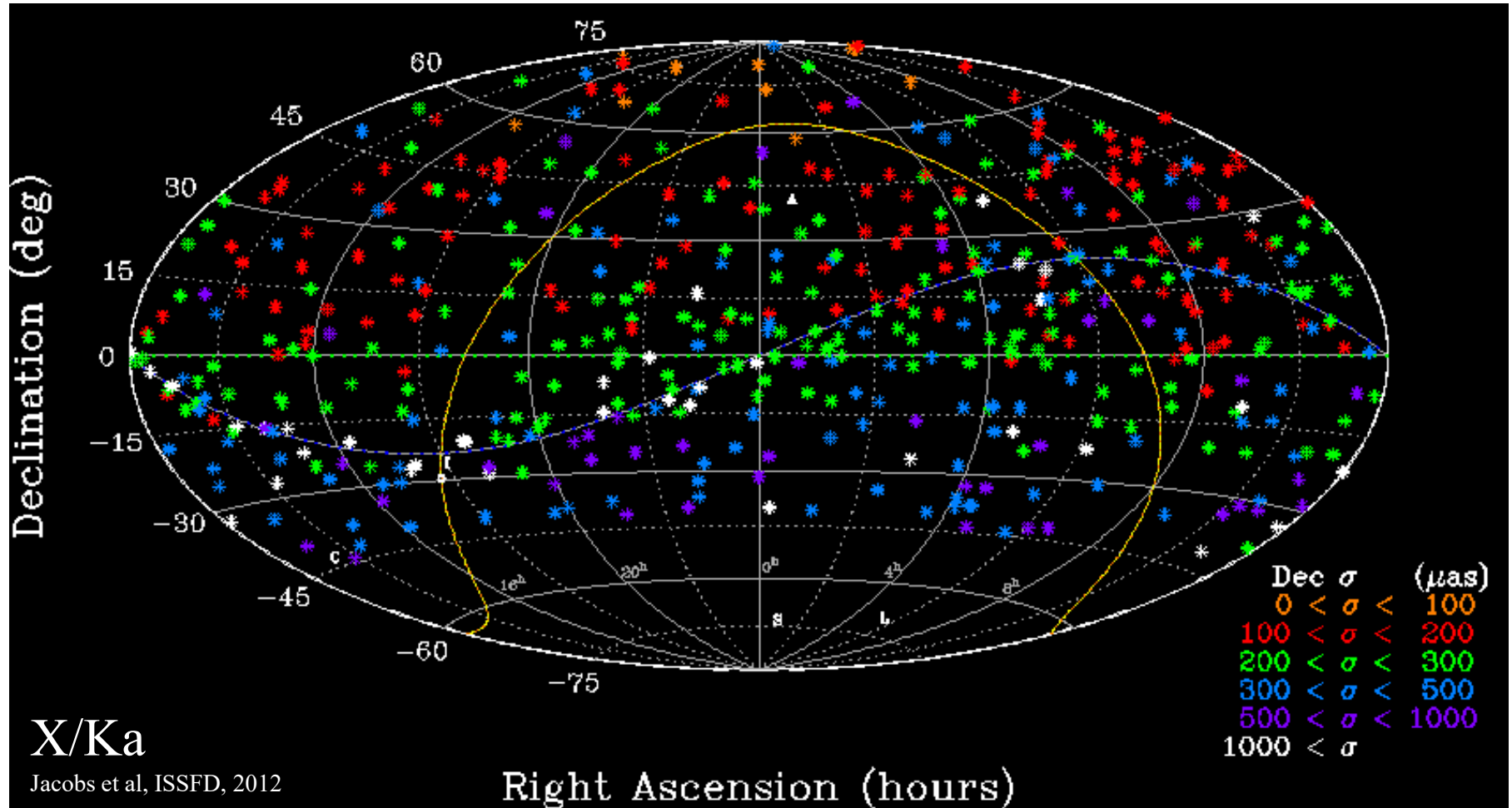
ESA's Argentina 35-meter antenna **adds 3 baselines** to DSN's 2 baselines

- Full sky coverage by accessing south polar cap
- near perpendicular mid-latitude baselines: CA to Aust./Argentina

Maps credit: Google maps

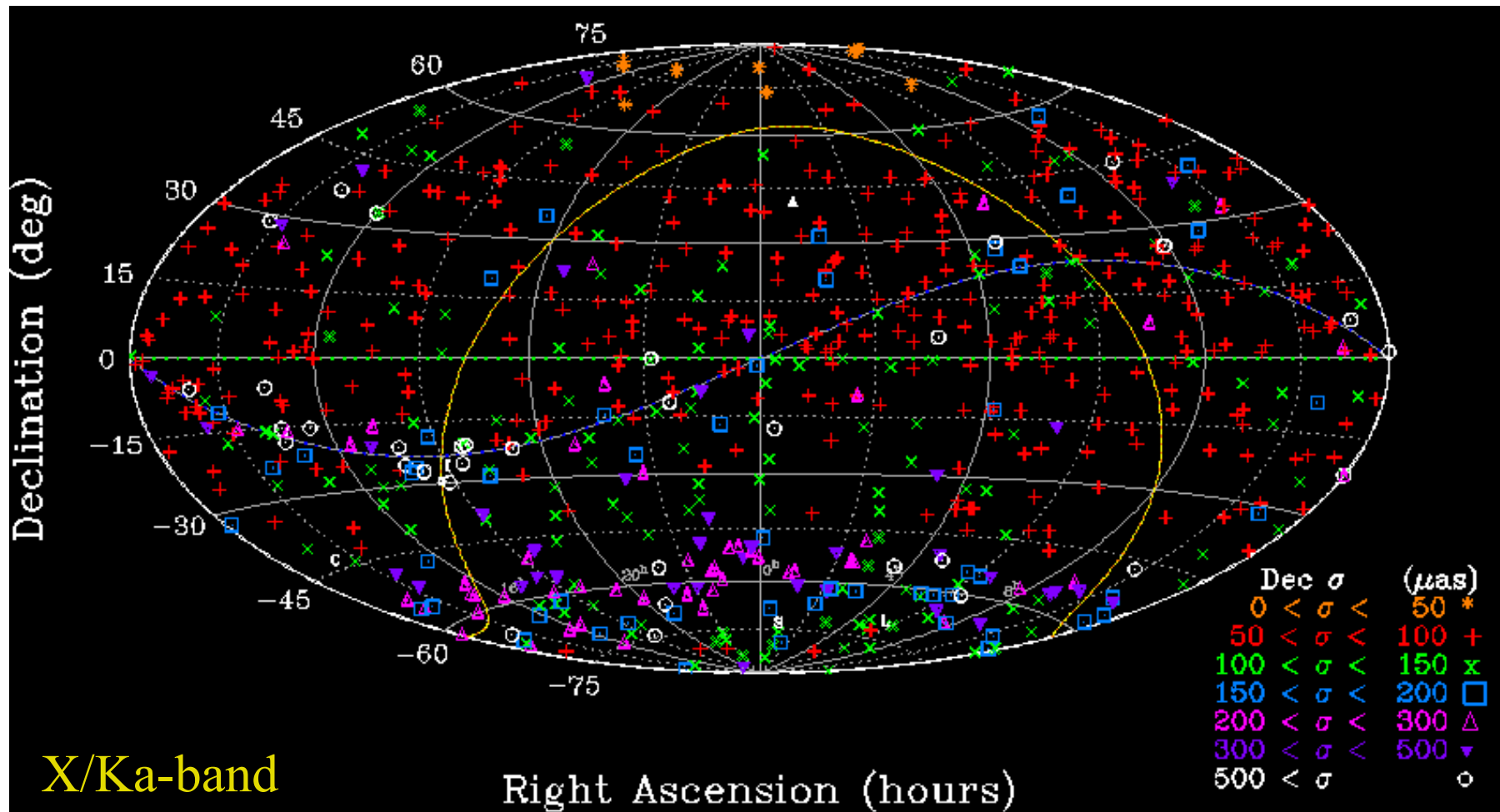
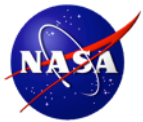


# NASA-only 32GHz Dec results: 482 sources



DSN only data before Oct 2012: Goldstone, CA to Madrid, Australia.  
Weak in the mid-south (Dec 0 to -45), no south Polar Cap (-45 to -90)





DSN: Goldstone, CA to Madrid & Canberra  
**+ ESA baselines: Malargüe to Canberra, Goldstone, Madrid**



# Outline

## I. Concepts and Background:

- A. What is a Reference frame? Concepts, uses, desired properties
- B. Networks: The instruments used to build the frame
  - ad hoc, VLBA, EVN, Global, NASA-ESA DSN, LBA, AuScope, etc.
- C. Brief history of Astrometry: The 'fixed' stars aren't so fixed.
  - 1. Precession, proper motion, nutation, parallax
  - 2. Invention of radio astronomy. VLBI's pursuit of (sub)milli-arcsecond accuracy.

## II. Celestial Frames built using VLBI

- A. Surveys: Single dish, connected array: JVAS, AT20G, and VLBI: VCS, LCS
- B. ICRF-1, ICRF-2: The IAU moves to from optical (stars) to radio (quasars)
- C. Higher frequency radio frames: K&Q (24 & 43GHz), XKa (32 GHz)

## III. The Path to the Future:

- A. Error Budgets: a tool for allocating resources for improvement
- B. Next-generation geodetic VLBI: Ultra-wide 2-14 GHz
- B. Case study: Path to Improved X/Ka (8.4/32 GHz) Frame
- C. ICRF-3: the next standard radio frame**
- D. Gaia: the return of optical



## III.C. ICRF-3

### 3<sup>rd</sup> generation International Celestial Reference Frame

#### Assessment of needs for ICRF-3

1. VLBA Cal Survey is most (2/3) of ICRF-2  
but positions are 5X worse than rest of ICRF-2
2. ICRF-2 is weak in the south
3. High frequency frames  
Fewer sources, weak in the south

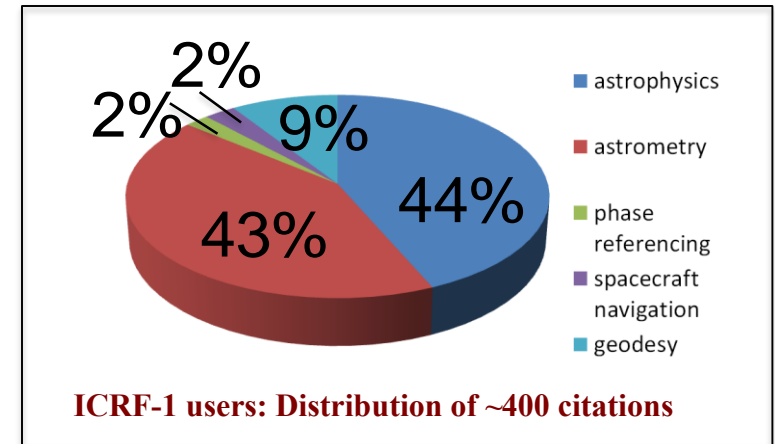


Figure Credit: Heinkelmann, EVGA, 2013

#### Goals:

1. Complete ICRF-3 by 2018  
in time for comparisons with Gaia optical frame
2. Competitive accuracy with Gaia  $\sim 70 \mu\text{as}$  (1-sigma RA, Dec)
3. Uniform precision for all sources. Implies improving VCS positions.
4. High frequency frames (K, XKa, Q?)  
Improve number, accuracy, and southern coverage
5. Maximize high quality optical-radio tie sources

**ICRF-2 reference: Ma et al, IERS, 2009.** <http://adsabs.harvard.edu/abs/2009ITN....35....1M>



# III.C. ICRF-3 Needs

- Uneven precision of current ICRF-2 VCS's 2200 sources (2/3 of the ICRF-2)
- VCS precision is typically 1000  $\mu\text{as}$   
5 times worse than the rest of ICRF2!

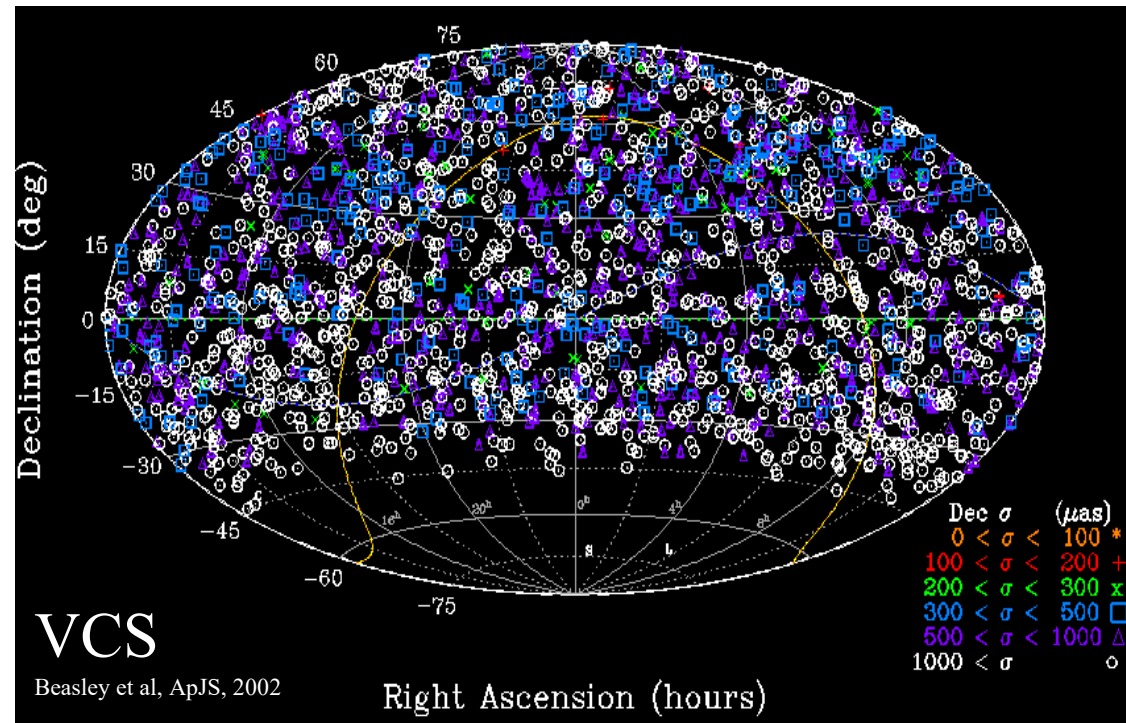
## Good news:

- VLBA Cal Survey-II  
VLBA approved 8 x 24-hour sessions  
to re-observe VCS sources.

PI: David Gordon, GSFC

8 passes completed

paper submitted to AJ Feb 2016



## ICRF2: VCS vs. Non

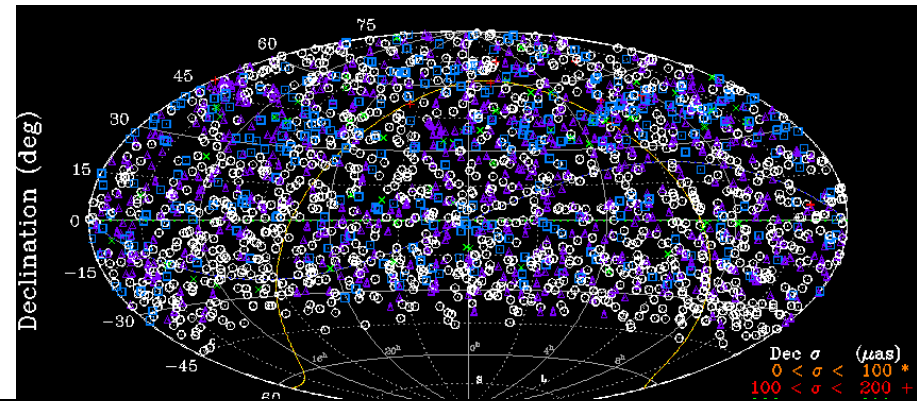
Item	VCS	non-VCS	factor	.
N_src	2197	1217	VCS 1.8X	better
median sessions	1	13	VCS 13X	worse
median observations	45	249	VCS 5.5X	worse
median time span	0	13 years	VCS	arbitrarily worse
median RA sigma	621	130 $\mu\text{as}$	VCS 4.8X	worse
median Dec sigma	1136	194 $\mu\text{as}$	VCS 5.9X	worse



# VLBA Calibrator Survey improvement

VCS-I:  $\sim 1$  mas precision  
for 2200 sources

credit: Beasley et al, AJ, 2002



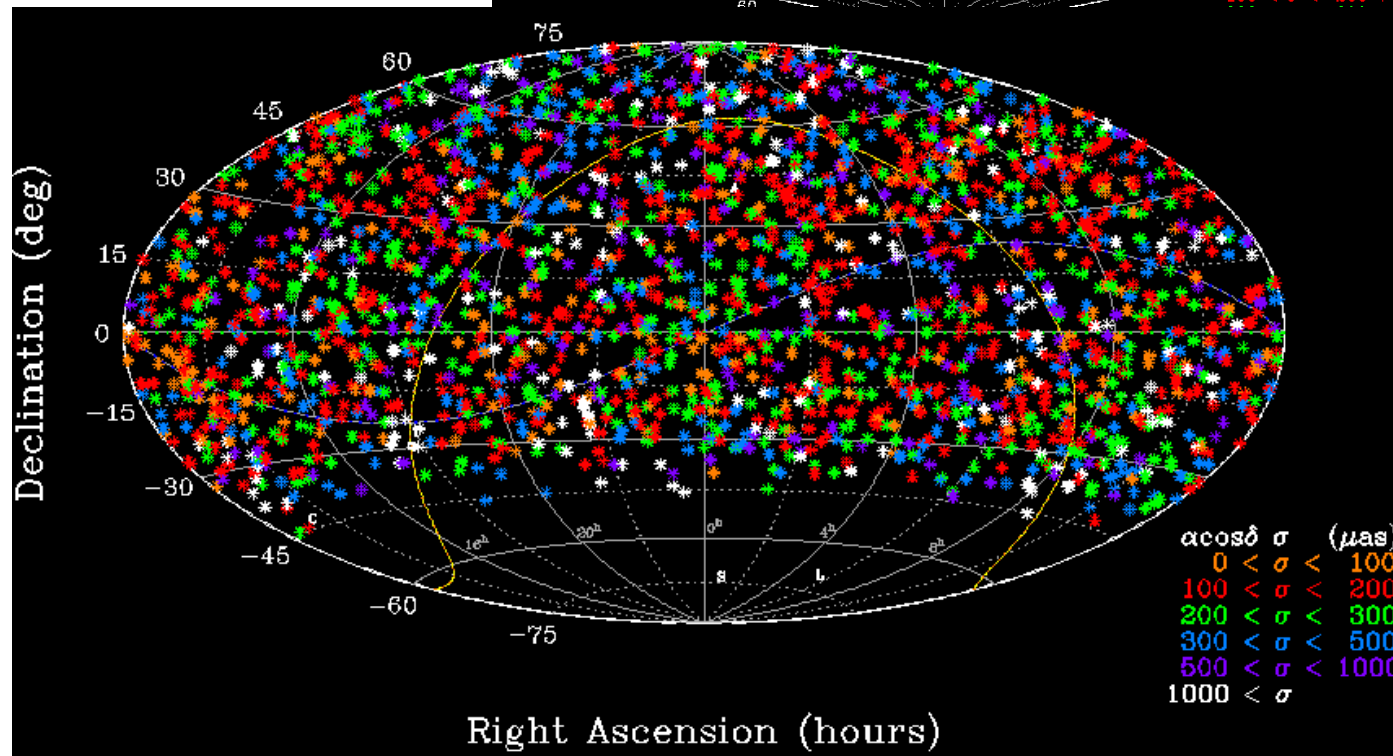
VCS-II:

RA 0.23 mas

Dec 0.39 mas

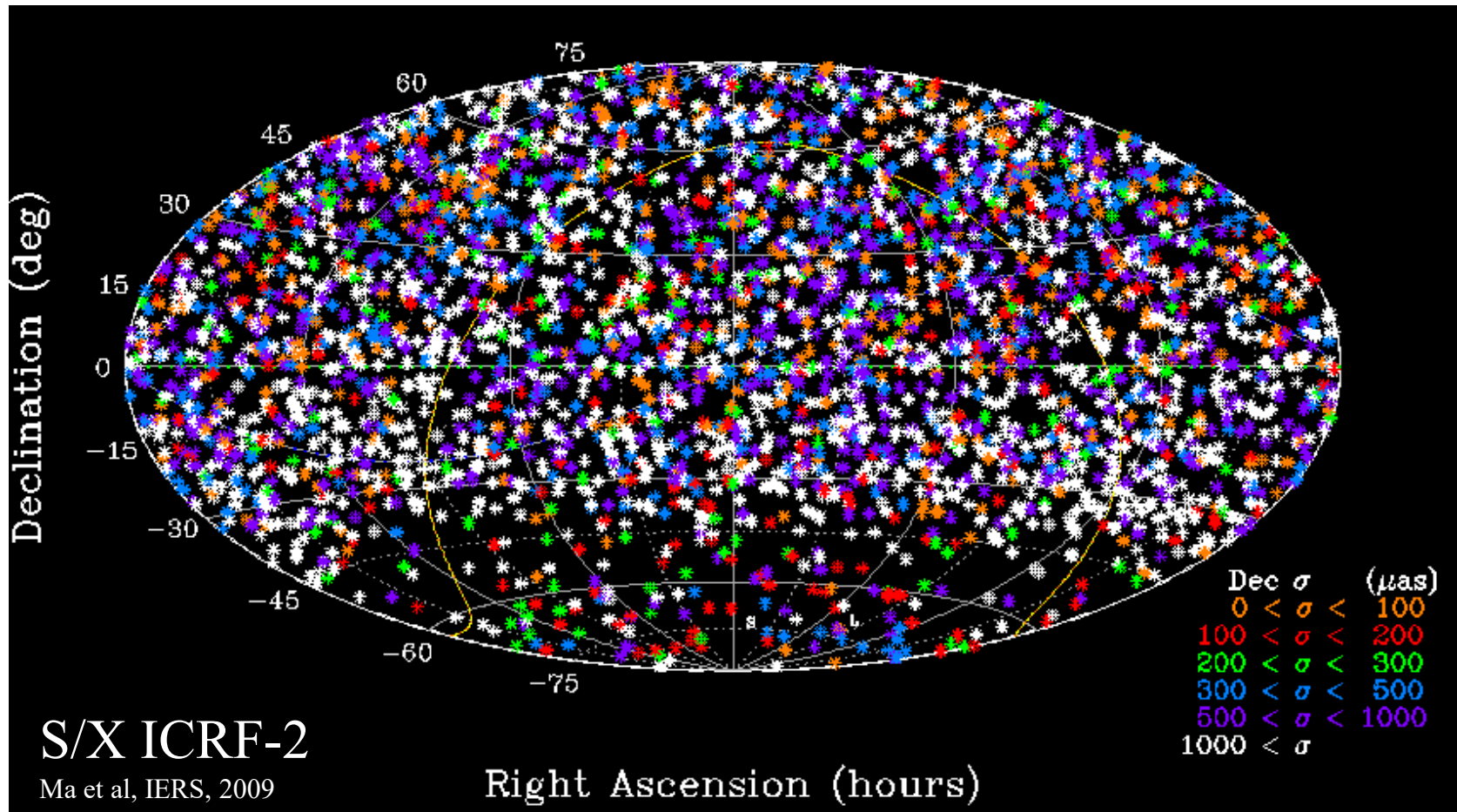
Improvement

$\sim 5$  times





# III.C. ICRF-3 Needs



Southern Hemisphere:

VLBI generally & ICRF-2 specifically lacks southern observations (Dec < -35 deg)

AuScope, Hobart, HartRAO exploring additional S/X observations